COST EFFECTIVE NAVAL SHIP SYSTEM DESIGN

Kenneth Wayne Shafer

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KENNETH WAYNE SHAFER

B.S.M.E., Purdue University

1969

SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREES OF

NAVAL ENGINEER

and

MASTER OF SCIENCE, SHIPPING AND

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ABSTRACT

COST EFFECTIVE NAVAL SHIP

SYSTEM DESIGN

by

KENNETH WAYNE SHAFER

SUBMITTED TO THE DEPARTMENT OF OCEAN ENGINEERING IN MAY 1976

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR

THE DEGREES OF NAVAL ENGINEER

AND

MASTER OF SCIENCE IN SHIPPING AND SHIPBUILDING MANAGEMENT

The Naval ship system design approaches used in recent years are described. The cost of ship system design effort expended in developing the contract plans and specifications for Naval ship acquisition is presented. The various elements of design effort contributing to the cost of Naval ship system design are identified.

A measure of the effectiveness of the level of effort expended on ship system design is developed by determining the cost of ship construction contract changes caused by deficiencies in the contract plans and specifications. The measure of effectiveness is combined with the cost of developing the contract plans and specifications and presented as a measure of the cost-effectiveness of Naval ship system design. The results include recommended optimal levels of Naval ship system design effort.

Thesis Supervisor: Clark Graham

Title: Associate Professor of Marine Systems

CHAPTER I

INTRODUCTION

The purpose of this chapter is to introduce the thesis. The reasons for conducting the research will be presented, the specific research question to be investigated will be stated, some special terminology will be defined, and the method of research will be described.

Reason for Conducting the Research

The United States Navy has been building and operating ships since the Revolutionary War. In spite of the vast shipbuilding experience of the United States Navy, shipbuilding projects have persistently experienced changes to the ship during construction. These changes have, in general, resulted in cost growth. It is rare that a ship is delivered to the Navy at a cost less than that estimated during the design phases of the ship acquisition project.

It should be emphasized that cost growth, or cost "overrun," is not a new problem. USS Constitution, "Old Ironsides," was authorized by the United States Congress in 1794, along with five other frigates. A total of $688,889 was appropriated for construction of the six ships [35]. The appropriation was based on several assumptions regarding

material availability. These assumptions proved to be erroneous within a few months. In particular, live oak for construction of these ships proved to be very difficult to get. In addition, changing requirements for the fledgling United States Navy resulted in cancellation of three ships, and diversion of some of the materials to the three ships remaining in the program.

The USS Constitution was launched in 1797, and subsequently delivered to the Navy at a final cost of $302,719 [35]. The delivered cost of three ships was slightly over $902,000, compared to $688,889 appropriated for six ships.

There are many reasons for cost growth in ship acquisition programs, including change in quantity, improvements, and correction of deficiencies in the ship system design. During the decade of the 1960's, the Ship Construction Navy (SCN) funding for new construction and conversion of Naval ships proved to be inadequate due to cost growth. The underlying reasons for the cost growth were investigated, and in 1969 the SCN Pricing and Cost Control Study [45] reported that inadequate contract plans and specifications were a major cause of the funding deficiency in the SCN program.

Commander A. C. Meiners, Jr., conducted an extensive study of the causes of cost growth in weapon systems acquisition in his 1974 George Washington University dissertation [36]. Meiners reported that incomplete plans and specifications at the time of contract award ranked second out of thirteen causes of cost growth; exceeded only by changes in

operational requirements causing a change in the weapon system, other than quantity. Change in quantity was not included among the thirteen causes investigated by Meiners.

The SCN Pricing and Cost Control Study recommended in 1969 that the Navy improve in-house design and specification writing capability. In addition, a formal evaluation of the entire ship specification was recommended. These recommendations have contributed to an increase in the scope of effort expended in Naval ship system design since 1969, and in the cost of developing contract plans and specifications. In spite of this increase in the scope and cost of ship system design effort, the Navy Marine Acquisition Review Committee (NMARC) recommended in January, 1975, that the Naval Sea Systems Command (NAVSEA) continue emphasis on increasing the scope of design effort going into contract plans and specifications [43].

Statement of the Research Question

Meiner's study, and the NMARC recommendation to continue increasing the scope of ship system design effort, suggest the question, "What is the correct scope of ship system design effort to expend in preparation of contract plans and specifications?" More simply stated, "How much design is enough?" Increasing the scope of ship system design effort should reduce the cost of changes caused by deficiencies in the contract plans and specifications, but the magnitude of cost savings resulting from increased design effort is

unknown. Spaulding and Johnson ask, "How much design is enough?" in their February, 1976, article on Ship Design Management, and state further that a measure of design cost effectiveness must be developed [51]. The object of this thesis is to develop a measure of Naval ship system design cost effectiveness in order to answer the question, "How much design is enough?"

Corollary questions related to the principal research question of "How much design is enough?" include:

1. Can acquisition cost be decreased by increasing the scope of design effort?
2. Does sufficient design capacity exist to support an increase in the scope of design effort?

The primary effort of this research will be to answer the principal question of "How much design is enough?" Corollary questions will be addressed to the extent feasible.

Special Terminology and Acronymns

This thesis will include language and acronymns unique to the Naval ship system design and acquisition process. The following definitions are provided to aid the reader.

Naval Ship System Design is the design effort expended between the initiation of feasibility studies and the completion of contract design, and does not include detail design performed by the shipbuilder after contract award.

Naval Ship System Design Deficiency is any technical or editorial error in the contract plans and specifications, including

conflicts, omissions, inconsistencies, engineering mistakes, infeasible weight and space allocations, and inadequate or unclear system definition.

Design to Cost is a design constraint imposed on the Naval ship system design process requiring the ship acquisition cost to be less than a specified amount.

Fly Before Buy is a constraint placed on the weapons system acquisition process prohibiting initiation of weapons production until prototype tests are satisfactorily completed. In the case of shipbuilding, true prototyping is not feasible; therefore, "Fly Before Buy" is complied with by extensive land based testing of critical subsystems during lead-ship construction, and by incorporating lead-ship detail design and construction experience into the follow-ship contract design.

Total Package Procurement is a weapon system acquisition strategy that places total responsibility for system design, construction, and demonstration of specified performance on the builder. The builder assumes all risks involved in sub-system development and integration and is required to provide a performance warranty on the finished product.

Concept Formulation/Contract Definition is a system design process developed to support the total package procurement acquisition strategy. The concept formulation phase is an in-house Navy effort to develop the system performance specifications. The contract definition phase is a three-step process during which competing contractors present plans for executing a system design, then execute the system design, and finally translate the design into detail specifications and a contract for production.

OPNAV is the office of the Chief of Naval Operations.

NAVSEC is the Naval Ship Engineering Center, Hyattsville, Maryland. NAVSEC performs

the function of Design Agent for the Navy, under the control of the Naval Sea Systems Command (NAVSEA).

Ship Acquisition Cost is the total cost of acquiring and delivering a ship system to the Navy including all payments to the shipbuilder, cost of all government design and development, government furnished material and information, fitting out, spare parts placed on board the ship, and post-shakedown availability work.

CG26 is the USS Belknap, formerly DLG26.

CGN36 is the USS South Carolina, formerly DLGN36.

CGN38 is the USS Virginia, formerly DLGN38.

FF1052 is the USS Knox, formerly DE1052.

FFG7 is the Patrol Frigate USS Oliver Hazard Perry presently under construction at Bath, Maine, formerly PF109.

TLR is a document jointly produced during the conceptual design phase by OPNAV and NAVSEC, establishing the Top Level Requirements for a ship system. The TLR describes the ship system performance characteristics in operator language and establishes design constraints and guidance.

TLS is a document developed by NAVSEC during the preliminary design phase, establishing the Top Level Specifications describing the ship system in engineering language.

ILS is Integrated Logistic Support; the planning of crew training, spare parts stockage, and off-ship maintenance and repair support for a ship.

RMA is Reliability, Maintainability, and Availability analysis involving the application of probability theory to systems to predict frequency and duration of system failures.

T&E is Test and Evaluation of systems, subsystems, and components for the purpose of system integration, and qualification for Naval service. Test and Evaluation ranges

from whole ship system testing during shakedown and operational evaluation, to shock testing of an individual equipment or component to qualify that equipment or component for Naval service.

DSARC is the Defense Systems Acquisition Review Council. DSARC evaluation and approval is required at least three times during every weapon system acquisition program. DSARC review occurs after concept selection, upon completion of preliminary design, prior to prototype (or lead-ship) construction, and prior to full scale production (follow-ship construction). Additional DSARC reviews may be scheduled at other checkpoints in the weapon acquisition program [32].

CDRL is Contract Data Requirements List; CDRL is a complete listing of all design data, drawings, technical manuals, operating instructions, etc., that the contractor is required to provide to the Navy as part of the contractual obligation.

GFE is Government Furnished Equipment. GFE includes all equipments and subsystems furnished to a shipbuilder by the government, and usually includes all weapon subsystems, sensors, command and control electronics, communications electronics, and all nuclear power subsystem components. Additional components and subsystems have been added to the above list for some ship acquisition programs. Occasionally the amount of GFE is less than listed above, as in the case of a Total Package Procurement.

GFI is Government Furnished Information and includes contract plans and specifications, and all technical documentation required for the shipbuilder to install and integrate GFE into an operational ship system.

Cost Estimating Classes are a system of classifying cost estimates by level of estimating quality. The cost estimate classes currently in use are: [42]

Class F: Quick cost estimates prepared in the absence of the minimum design and

cost information package, based on gross approximate parameters. Typically, estimates are generally calculated by merely escalating to current dollars an empirical cost for a similar ship and adding factors for expected changes in design, accounting procedures or other economic considerations.

Class E: An estimating process when cost and design information is developed by use of a computer model which grossly determines ship specifications from a given set of input characteristics. In general, the output cost and design information is calculated from estimating relationships through a series of equations while payload type items such as electronics, ordnance, etc., are costed by a shopping list technique within the model.

Class D: An estimate of a lower quality than a Class C estimate due to an insufficiency in the design, procurement or cost information primarily the result of a need for an estimate before such information can be further developed to justify a C classification. Such early estimates are usually exploratory in nature and are prepared to perform trade-offs and cost effectiveness analysis, to establish notional ship characteristics and for costing the program objectives in the outyears where there is an absence of sufficient design development.

Class C: The highest level of cost estimates attainable in the planning, programming and budgeting process. A Class C estimate is the recommended level for estimates of cost to be used in the budget submission especially at the Congressional level, preferably for the NAVCOMPT and OSD/BOB submissions and whenever feasible for the program objective estimates for the current budget year.

Class B: An estimate prepared to validate the "reasonableness" of cost estimates received from contractors or government shipyards. Prepared immediately prior to a bid opening or upon receipt of an initial cost estimate from a Naval shipyard.

Class A: An extensive cost estimate prepared to validate an end cost estimate; for determination of a "fair and reasonable" price for comparison to contractors prices; but primarily for contract negotiation purposes. It is always prepared in the post-budget process and generally prior to a bid opening or scheduled negotiation of fixed price incentive or cost plus type contracts. This level of cost estimate requires contract plans and specifications and a detailed contract design weight estimate as inputs from the design process.

Method of Study

Development of a measure of ship system design cost-effectiveness requires the development of a measure of cost and a measure of effectiveness. The cost of ship system design is readily available for several classes of Naval ships. Measuring the effectiveness of ship system design is more difficult. The military worth per dollar invested in acquisition and ownership is a measure of ship system design effectiveness; however, measuring the military worth of a Naval ship in terms of dollars presents formidable problems. It is theoretically possible to measure the military worth of a Naval ship through the application of multiattribute utility theory, but the practical application of multiattribute utility theory to a system as complex as a multimission Naval ship is an extremely large undertaking, and is beyond the scope of this thesis.

This thesis will concentrate on one measure of ship system design effectiveness; the cost of contract changes caused by errors, omissions, inconsistencies, or other

deficiencies in the contract plans and specifications produced by the ship system design effort.

Three distinctly different approaches to Naval ship system design have been used since 1960. Each of these approaches will be described, and the differences will be examined. Ship system design tasks common to all three approaches will be identified. The cost of the design tasks common to the three different approaches will be presented for several classes of Naval ships. The cost of contract changes required to correct design deficiencies in the contract plans and specifications will also be presented. With the ship system design cost and the cost of correcting ship system design deficiencies thus established, a cost-effectiveness function for those design tasks common to all three approaches will be developed. The cost effectiveness of design tasks not common to all three design approaches will not be determined.

Organization of Thesis

Chapter II will discuss three different approaches to Naval ship system design, and will identify the work tasks common to all three approaches.

Chapter III will present the cost of ship system design for several classes of Naval ships. The cost of work tasks not common to all three design approaches will be identified and segregated from total ship system design costs. The cost of the design tasks common to all three

approaches will be adjusted for inflation by applying a cost index based on the cost per man-day of design effort. The design cost will be presented in constant Fiscal Year 1976 dollars.

The acquisition cost of the lead ship of each class under investigation will be presented, along with the average acquisition cost per ship for each class. The acquisition cost will be adjusted for inflation by applying a shipbuilding cost index developed from material and labor cost indices. The acquisition costs will be presented in constant Fiscal Year 1976 dollars.

The cost of ship system design elements common to all three design approaches will be expressed as a percentage of ship acquisition cost for each ship class, in order to take into account differences in ship system complexity. Ship system acquisition cost is proportional to ship system complexity, and ship system design cost is proportional to ship system complexity. By expressing ship system design cost in percent of ship system acquisition cost, the effect of ship system complexity is taken into account for a given type of ship. Combatant ships and auxiliary ships will be treated as disparate types.

Chapter IV will discuss the method of collecting data on the cost of contract changes caused by deficiencies in the contract plans and specifications, and present the data collected. The cost of changes caused by design deficiencies will be adjusted for inflation by applying the ship

building cost index from the chronological midpoint of ship construction to mid-1976. The cost data will be presented in constant Fiscal Year 1976 dollars and in percent of lead ship and average ship acquisition cost.

The cost of changes caused by deficiencies in contract plans and specifications is proportional to ship system complexity. The effect of ship system complexity is taken into account by expressing the cost of changes in percent of ship acquisition cost, for a given type of ship. Combatant and auxiliary ships will be treated as disparate types.

The information presented in Chapters III and IV will be combined to develop a Naval ship system design cost-effectiveness function for those design tasks common to the three design approaches used since 1960. The return from increased scope of effort expended on these common tasks of ship system design will be quantitatively assessed, and the level of effort at which marginal return in terms of reduced changes cost is equal to marginal cost in terms of increased design cost will be established. That level of effort at which marginal return is equal to marginal cost, is the correct amount of effort to expend on development of contract plans and specifications during the ship system design process.

CHAPTER II

APPROACHES TO NAVAL SHIP SYSTEM DESIGN

Introduction

This chapter of the thesis will review the different approaches used in the Naval ship system design process over the past 15 years. The prominent features of each approach will be presented and compared as background for the development of Naval ship system design costs in Chapter III and Naval ship system design effectiveness in Chapter IV. The design tasks common to all three approaches will be identified.

Three distinctly different approaches to Naval ship system design have been used during the past 15 years. Prior to about 1965, the design approach was what is now called the "Conventional" approach [3, 19, 37]. During the mid-1960's, the total package procurement (TPP) weapon system acquisition approach was developed, resulting in the ship system design approach called Concept Formulation/ Contract Definition (CF/CD) [1, 31, 48, 49, 50, 52]. The CF/CD approach was terminated as the decade of the 1970's started, and replaced by the present approach to ship system design. The prominent features of each approach are discussed in this chapter. The discussion is intended only to

highlight the prominent features of each approach for comparison purposes, and is not intended as an exhaustive treatment of the subject of Naval ship system design. The reader interested in more detail should consult the references cited.

Figure 1 provides a comparison of the terminology and sequence of events as practiced in each of the three approaches [19]. It should be noted that the detail design and working drawings are produced by the shipbuilder in all three approaches. This thesis is concerned with system design as opposed to detail design. Ship system design encompasses all the design activity from the beginning of feasibility studies through the completion of contract design.

Present Naval Ship System Design Approach

Figure 2 illustrates the key features of the present ship system design approach, and the sources of these features. In essence, the present approach is an attempt to combine the best of conventional and CF/CD approaches, and at the same time incorporate additional desirable features. The objectives, products, and process of each phase of the present approach are summarized in Figure 3 [51].

Under the conventional ship system design approach, the "Customer's Requirements" were provided to NAVSEC in the form of "single sheet characteristics." Actually, this document would consist of three to ten pages and was a

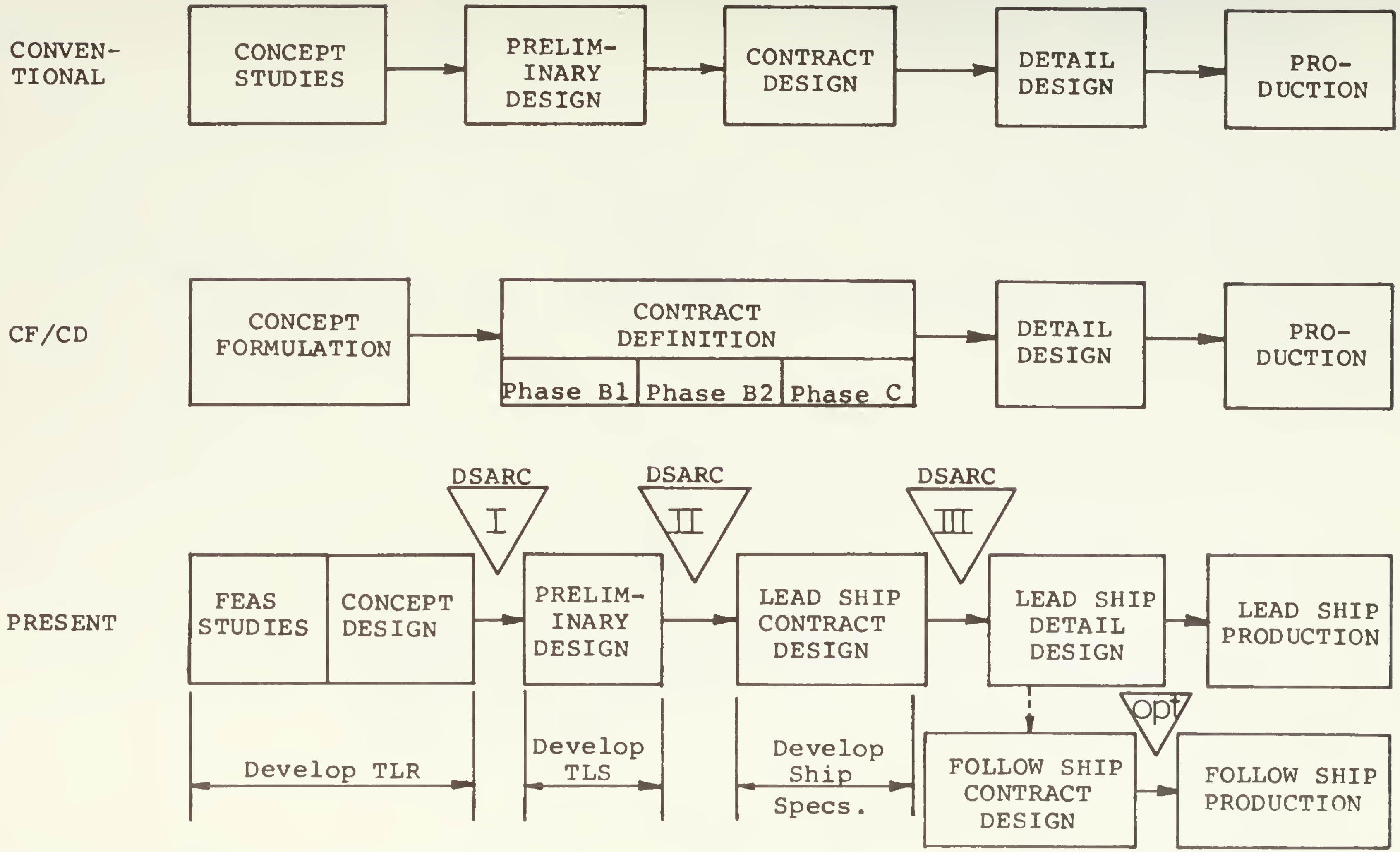

Figure 1. Comparison of Naval Ship System Design Approaches.

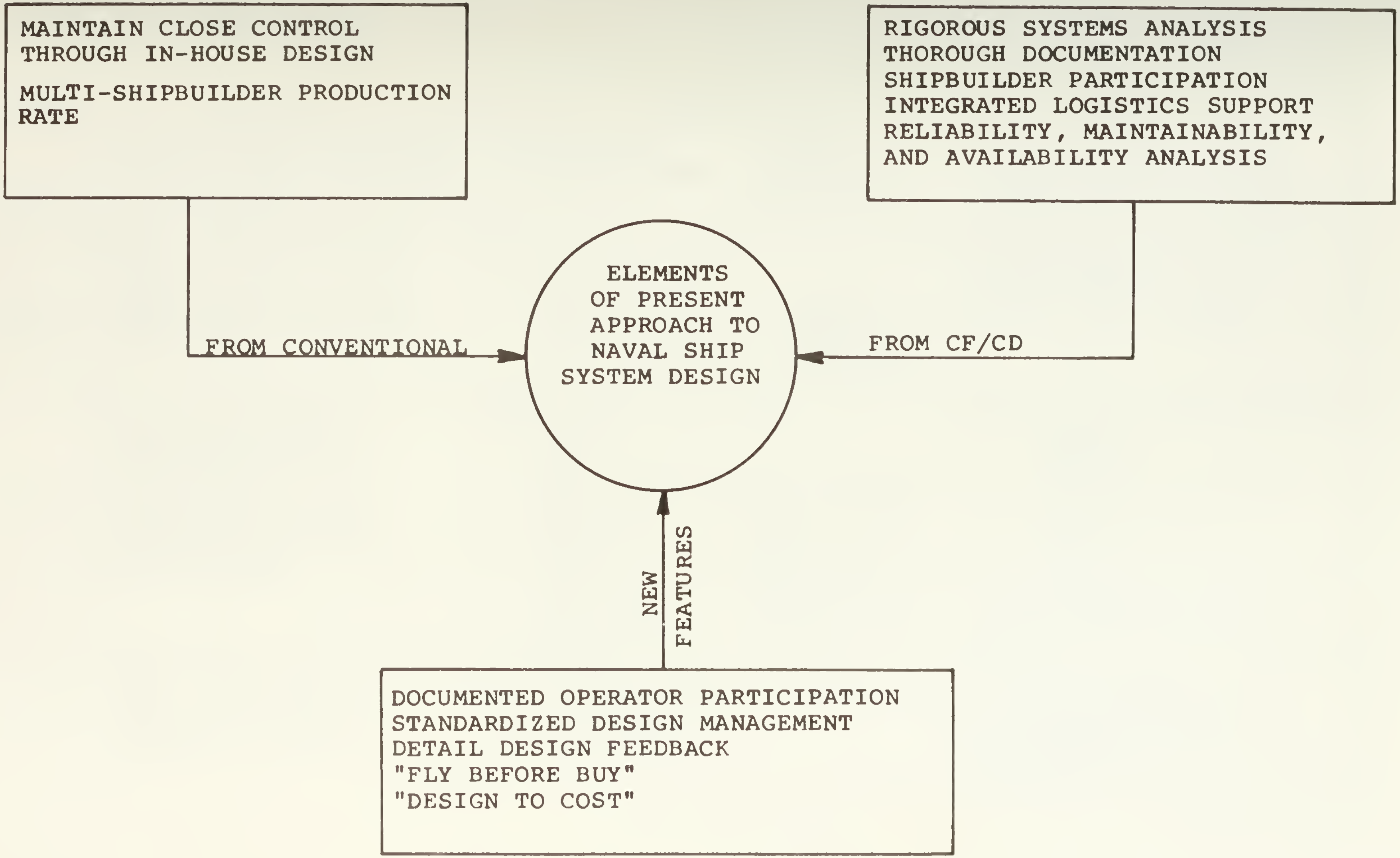

Figure 2. Elements of Present Approach to Naval Ship System Design.

PHASE	OBJECTIVES	PRODUCTS	PROCESS
FEASIBILITY STUDIES	a - to define a series of feasible ships, with associated production costs, which meet, or approach, initial performance requirements. b - to achieve a balance between operational requirements (based on companion military effectiveness studies) and production costs (i.e., to determine most operationally cost effective alternative). c - to select, from the alternatives defined, a ship for Conceptual Design ("Concept Selection"). d - to assure definition of alternative ships to the level required for a Class E (Class F for less reliable results) cost estimate. e - to identify the major technical risks associated with alternative ships. f - provide the basis for setting a design-to-cost target.	a - "concept selection" b - Class E or F cost estimate c - definition of payload d - synthesis model weight (1 digit level) space allocations (developed by hand if synthesis model not available) e - general arrangements drawings (if a "hand study") f - complement (officers, CPO's and enlisted) g - type of machinery & number of propellers h - speed i - installed electric power j - general ship geometry including total ship volume and area estimates Above items are included in the Feasibility Study Report.	a - small group effort (3-4) people b - synthesis model (50-300 ships or hand (2-30 ships) analysis (5% accuracy on ship weights) c - cost program operates on synthesis hand study outputs d - general arrangements drawings developed with hand studies e - performance in terms of speed, endurance, major payload items and special features (side protection etc.) f - relative accuracy and consistency vs. "absolute" nature of results is stressed g - for non state-of-the-art designs, basic design methodology must be developed before initiating Feasibility Studies
CONCEPTUAL DESIGN	a - to provide a technical baseline (Conceptual Baseline (CBL)) for DSARC I for new major combatant or developmental designs. b - to assure definition of the ship to the level required for a Class D cost estimate (provides a basis for setting a design-to-cost goal by OPNAV). c - validation of feasibility study results - provision of a firm baseline for initiation of Preliminary Design (size, weight and cost should only be "reduced" in Preliminary and Contract Designs). d - initial resolution of major technical risks identified in the Feasibility Studies.	a - Class D cost estimate b - draft TLR, TLS Section 2 c - Conceptual Baseline (CBL) Package 1. design rationale 2. general arrangement drawings 3. weight estimate at 3 digit level 4. body plan 5. transverse and damage stability seakeeping analysis 6. speed/power curve 7. structural midship section (optimal) 8. tentative combat system block diagram 9. weapons equipment list 10. manning list 11. equipment list 12. propulsion/propeller analysis 13. machinery arrangement 14. power analysis & tentative generator selection 15. auxiliary machinery analysis 16. electronics space and topside arrangements Above items included in the Conceptual Design Report	a - larger group (15-25 people) b - continual interaction with TLR development (military effectiveness studies in parallel) c - ship sized on an "absolute" basis vs. "relative" basis in Feasibility Studies d - major subsystem trade-offs e - development of credible space/weight budget f - emphasis on resolution of major technical risks
PRELIMINARY DESIGN	a - to provide a technical baseline (Functional Baseline (FBL)) for DSARC II. b - to assure definition of the ship to the level required for a Class C cost estimate (lowest budget quality estimate). c - to achieve a complete engineering description of an integrated ship system such that the basic ship size and definition will not change during Contract Design. d - to achieve functional definition of integrated subsystems selected for optimization of total ship performance and cost. e - to select final design criteria for whole ship entity characteristics such as noise and ship protection consistent with cost and performance optimization of the total ship. f - confirm the design-to-cost goal. g - validation of selected subsystems.	a - Class C cost estimate b - TLS c - Planning Documents 1. ILS Plan 2. Combat System Management Plan 3. Land Based Test Site Management Plan (if required) 4. T&E Master Plan d - FBL Package 1. Master Equipment List (MEL) 2. Preliminary Ship Manning Document 3. Noise Evaluation & Ship Protection Analysis 4. RMA Analysis 5. Structural Analysis & Drwgs 6. General Arrangements 7. Space Arrangements 8. Access Studies 9. Habitability Studies 10. Weight Estimate 11. Stability Analysis 12. Resistance/Seakeeping/ Maneuvering Analysis & Model Tests 13. Propulsion System Analysis 14. Electrical System Analysis 15. Machinery & Auxiliary Arrangements 16. Preliminary descriptive system analysis 17. HVAC Requirements & Diagrammatics 18. Deck & Weapons Systems Analyses & Drawings 19. Ship Control Analysis 20. Combat Data Document 21. Combat System Block Diagrams & Analyses 22. Combat System Description 23. Combat System Space Arrangements 24. IC, Navigation, Radar, IFF & Sonar Analysis 25. Antenna Arrangements & Topside Design Performance Assessment 26. External Communications & Command and Control Description	a - Major effort (20000 MD) b - Design-to-cost trade-off analysis "design review" and selection 1. Subsystems Hull Form General Arrangements Electric Power Propulsion System Auxiliary Systems HVAC Deck & Weapons Handling & Replenishment Systems Ship Control Structures Ship Manning Weapons & Sensors Antennas & Topside Design Performance 2. Ship Entity Characteristics Noise and Vibration Ship Protection ILS/RMA c - Intensive ship system level integration/optimization analysis d - Focus on TLS development e - Combat Systems integration with ship system f - "Design freeze" at completion of subsystem and ship entity characteristics selection
CONTRACT DESIGN	a - to provide a technical/contractual baseline (Allocated Baseline (ABL)) suitable for DSARC III. b - to assure definition of the ship to the level required for a Class B cost estimate (support establishment of a design-to-cost ceiling). c - complete translation of the FBL "engineering" definition of the ship to a contractual "biddable package." d - general validation of FBL ship system through increased level of definition.	a - Class B cost estimate b - Ship Specification c - Planning Documents for Detail Design & Construction Phase (further developments of plans listed under Preliminary Design Products). d - ABL Package (Contract, Contract Guidance and Study Drawings with selected studies and guidance documents). e - "Backups" analytical studies f - GFE procurement specifications g - GFI requirements definition h - Contract Data Requirements Package i - Preliminary Operational Stations Booklet j - Mock-ups	a - major effort b - emphasis on: 1. preparation of ship specifications 2. CDRL package preparation 3. contractability and producibility of ABL package 4. GFE/GFI definition c - detailed subsystem/equipment definition d - final system performance validation by model tests e - detailed space layouts f - mock-up evaluation of critical spaces g - intensive final package review and adjudication effort h - formal configuration control * Destroyer type

Figure 3. Present Approach to Naval Ship System Design.

brief description of the type of ship desired, including specification of speed, endurance, weapons and sensors, crew size, and frequently the type of propulsion plant [37]. During the conventional design process, the characteristics were sometimes modified as a result of design trade-off studies. The trade-off studies were guided by the Ship Characteristics Board (SCB), a group of high-ranking officers in OPNAV. The overall ship characteristics were approved by the SCB during preliminary design. The membership of the SCB was not static during the time between completion of preliminary design and delivery of the ships to the fleet; consequently a Board comprised of different people was sometimes unhappy with the ships when the ships were delivered.

Beginning with the Guided Missile Frigate (FFG7) in 1971, a Top Level Requirement/Top Level Specifications procedure was implemented as a replacement for "single sheet characteristics." The Top Level Requirements (TLR) document is a detailed description of the capabilities to be provided; and, in addition, contains considerable philosophy about factors to be considered as governing during trade-off studies [41]. The TLR document is produced in rough draft form by the Chief of Navl Operations (OPNAV), then sent to the Naval Ship Engineering Center (NAVSEC). Operators and designers jointly produce the final draft in smooth form during conceptual and preliminary design. The final form is a document of 100 pages or more and describes in detail

the ship system characteristics and capabilities in the language of the operator.

The Top Level Specifications document is produced by NAVSEC during preliminary design. This is a complete 200-300 page engineering description of the ship system characteristics and capabilities, and is written in engineering language [41]. Upon completion of preliminary design, the TLR/TLS documents are carefully reviewed and differences adjudicated. Both documents are <u>signed</u> by NAVSEC and OPNAV, thus forming a "contract" between the engineers and the operators. The effort expended in developing the TLR/TLS documents is cooperative in nature and specifically for the purpose of ensuring that the ship to be built is what the Operating Navy wants, as well as documenting operator participation in conceptual trade-off studies [18]. Extensive documentation of all trade-off studies is maintained, and systems engineering efforts are likewise extensive in the joint effort to provide the "best" ship design to meet the operator's needs. Virtually all "what-if" questions are explored and the results documented to aid future review of the process followed in selecting the ship characteristics.

After the TLR/TLS documents are signed, the design proceeds into the contract design phase, which also differs substantially from the conventional design process in that ship designers are "farmed-in" from a designated lead shipbuilder and an alternate lead shipbuilder as advisory participants in the contract design phase. The purpose of

shipbuilder participation is to enhance producibility and reduce acquisition cost. The completion of contract design is followed by award of a contract for building the lead ship, with the detail design being performed by the lead shipbuilder or his design agent. Detail design work is done under a contract separate from the shipbuilding contract. The detail design and construction experience gained during lead-ship construction is then "fed-back" to NAVSEC and incorporated in the follow-ship contract design.

A design management team of six to eleven personnel are dedicated full time to the design effort from initiation of conceptual design through completion of contract design in order to provide continuity from one design phase into the next phase, and to facilitate the close control necessitated by "Design to Cost" constraints. Design optimization is based primarily on minimum acquisition cost. Life cycle costs are given due consideration when future costs can be predicted with confidence.

Control of technical risk is provided by detailed plans for ship test and evaluation (T&E) in parallel with the design effort [44]. The objective is to apply the "Fly Before Buy" concept to the extent feasible in ship acquisition. High risk subsystems are identified, and detailed plans for testing and evaluating those high risk items are developed. For example, the FFG7 design included plans for land based test facilities for the combat subsystem and

propulsion subsystem. Land based tests are conducted while the lead ship is under detail design and construction.

Design elements involving crew training, maintenance support concepts and facilities, and spare parts support are also developed in parallel with the ship design under the present approach. This effort is termed Integrated Logistics Support (ILS), and is described more fully in references [15, 33, 34, 44].

The products of each design phase are the results of extensive trade-off studies and systems engineering efforts. The resulting design is better documented, more thoroughly studied, and more producible than under the conventional approach. High risk subsystems are identified and tested before proceeding with follow ship construction. Logistic support is addressed early in the ship system design process.

Concept Formulation/Contract Definition (CF/CD) Approach

A new way of producing ship system designs was introduced in the mid-1960's along with the Total Package Procurement (TPP) concept. The method is called Concept Formulation/Contract Definition (CF/CD) [1, 31, 48, 49, 50, 52]. "In-house" Navy studies during the concept formulation phase identify the basic performance characteristics to be provided by the ship. At first glance this seems similar to the concept design phase of the conventional ship design process; however, this is not the case. Concept formulation is concerned with identifying and describing the performance

requirements as opposed to describing a ship system that will meet OPNAV specified requirements. The concept formulation output provides some basic guidance as to what type of ship is desired; however, the guidance is deliberately minimized in order to allow competing contractors the widest possible latitude in producing a design to meet the requirements.

The most significant difference from conventional concept studies is extensive application of systems analysis in defining the performance requirements to be met. Existing design criteria are challenged and examined in depth before being accepted as valid. The optimization criteria is to maximize life cycle cost-effectiveness.

The output of concept formulation is a Request for Proposals (RFP) for contractors interested in competing for the award of a TPP contract of large magnitude. The RFP is a request for contractors to present detailed plans for performing a complete ship system design based on the specified performance characteristics. The responses are prepared by the contractors at no cost to the government and are evaluated by the Navy. Two or more contractors are then awarded fixed price contracts to develop the contract definition; a complete shipbuilding proposal including contract plans and specifications, detailed construction plans, and a complete analysis of life cycle cost.

Each contract definition output is evaluated by the Navy on the basis of technical excellence, planning, and

costs. The most cost-effective proposal becomes the basis of a TPP contract after incorporation of particularly attractive portions of the other proposals.

The products of the CF/CD concept formulation phase were roughly equivalent to the feasibility studies products shown in Figure 3. The contract definition phase B-1 products were roughly equivalent to the conceptual design products shown in Figure 3. The contract definition phase B-2 products were roughly equivalent to the preliminary design products shown in Figure 3. The contract definition phase C products were roughly equivalent to the contract design products shown in Figure 3.

The "Objectives" and "Process" columns shown in Figure 3 are somewhat different for the CF/CD approach, but the products and design tasks performed are essentially the same for CF/CD as those shown in Figure 3 in the "Products" column.

"Conventional" Naval Ship System Design Approach

The approach taken in conventional ship design varied from design to design, depending on the similarity between the ship under consideration and existing ships. If the new ship was to be an evolutionary development of an existing type, it was frequently possible to improve and update a "parent design," thereby reducing significantly the design effort required. On the other hand, a revolutionary or radically different ship type might require an extensive research and development effort.

The principal objective of conventional conceptual design was to determine the range of feasible alternatives, to conduct gross characteristics trade-off studies, and to select the optimum alternative. The gross characteristics such as length, beam, draft, and power, were established in conceptual design. Principal weapons and sensors, number of propellors, type of propulsion and required speed, and crew size were usually specified by OPNAV.

Many of the operations performed in the conventional conceptual design phase were redone in the conventional preliminary design phase, but in greater detail and with better information. Areas not considered in the conceptual design phase were examined. Particular attention was given to the problems of area and volumetric adequacy, and ship arrangements, which were given only a rough check in the conceptual design phase. With the development of hull lines, ship model tests were initiated for more accurate determination of the speed-power, maneuvering, and seakeeping characteristics of the design. The end products of the preliminary design usually included: [37]

1. General arrangement plans.
2. Lines and body plan.
3. Appendage plan.
4. Hydrostatic curves.
5. Midship section and special structural plans.
6. Weight, VCG and LCG estimates, tankage, etc.

7. Speed-power estimate, propellor performance, and model test results.
8. Stability estimates, both intact and damaged.
9. Protection plans, including ballistic, underwater, nuclear, and shock and blast protection.

The emphasis of conventional preliminary design was to provide a complete engineering description of the ship.

The conventional contract design phase followed preliminary design and carried the design through another complete cycle of even greater detail and finer definition. Detailed shipbuilding specifications were prepared, and as many as a hundred contract drawings and contract guidance plans would be produced. The emphasis was to produce a "biddable package," i.e., enough detail to allow prospective building contractors to prepare accurate bids. However, compared to CF/CD or the present approach to designing ships, the conventional approach was a lower level of effort, produced entirely "in-house" by NAVSEC designers.

The conventional conceptual design phase essentially combined the feasibility studies and conceptual design phases shown in Figure 3. The conventional conceptual design approach did not include the draft TLR or TLS section two shown in the "Products" column of Figure 3. Also, the dedicated management team concept was not used with the conventional ship system design approach.

The conventional preliminary design phase was similar to the present approach, but the following products, shown in Figure 3 for preliminary design under the present approach were not included:

TLS

Planning Documents

ILS Plan

Combat System Management Plan

Land Based Test Site Management Plan

T&E Master Plan

RMA Analysis

Also, the manning requirements, noise evaluation, and shock (ship protection) requirements did not receive the level of attention provided by the present approach.

The conventional contract design phase included the same products as those shown in Figure 3 for the present approach, with the exception of the planning documents for detail design and construction. Under the conventional approach to Naval ship system design these planning documents were prepared outside the design group, and the cost of preparing detail design and construction plans was not considered a design cost. Also, backup analytical studies were not as extensive under the conventional approach, as compared to the present approach.

Comparison of Approaches to Naval Ship System Design

Extensive application of systems analysis techniques, team management, ILS, T&E, RMA, and thorough documentation of results was not employed in conventional ship system design. In general, the ships were "optimized" to a specified level of performance. Cost was an important but not overriding consideration. The results were certainly adequate but hardly "optimal" according to a systems analysis definition. Advancing technology, increasing complexity of combatant ships, and the development of systems analysis techniques provided both the impetus for, and method of, developing a more thorough and more rigorous approach to Naval ship system design.

The introduction of "Design to Cost" and "Fly Before Buy" acquisition strategies have resulted in some features of the present design approach that were not part of conventional or CF/CD approaches. The TLR/TLS procedure and detail design feedback into the follow-ship contract design are examples of new features.

Design tasks included in the present and/or CF/CD approaches, but not included in the conventional approach include:

1. Dedicated design management team.
2. ILS planning.
3. RMA tasks.
4. T&E Planning.

5. TLR/TLS development.

6. Systems analysis.

Other design tasks that today receive much greater attention than under the conventional approach include:

1. Ship manning analysis.

2. Noise analysis.

3. Cost analysis.

These three tasks, together with RMA and systems analysis tasks comprise the bulk of the "systems engineering" effort expended in the present ship system design approach.

All of the design tasks performed in conventional ship system design are also performed under the CF/CD and present approaches; therefore, the design tasks associated with the conventional approach will be used as a baseline defining those design tasks common to all three approaches. Dedicated team management, ILS and T&E Planning, TLR/TLS development, and "systems engineering" tasks were not included in the conventional ship system design approach; therefore, the cost of performing these tasks will be deleted from the total ship system design cost of the present and CF/CD approaches in order to place all three approaches on a common cost basis.

Summary and Conclusions

Three different approaches to Naval ship system design have been reviewed. The design tasks common to all three approaches have been identified as those design tasks

performed under the conventional approach. The design tasks performed under the conventional approach have been established as a baseline for comparison of ship system designs produced by different design approaches.

The baseline design tasks are the hard-core engineering effort, that is, the part of design effort that contributes to the technical accuracy of contract plans and specifications. The non-conventional design tasks not included in the baseline tasks may have a very large pay-off in terms of optimizing the gross characteristics of the ship, reducing life cycle costs, and ensuring smooth introduction into the operating fleet; however, the nature of these non-conventional tasks clearly indicates that non-conventional design tasks do not significantly improve the technical accuracy, clarity, or consistency of the contract plans and specifications.

The effectiveness of the hard core engineering effort (conventional design tasks) can be measured by the cost of contract changes caused by deficiencies in contract plans and specifications. This thesis will not attempt to measure the effectiveness of non-conventional design tasks.

Chapter III will present the cost of producing several Naval ship system designs. The cost of non-conventional design tasks, corrected for inflation, will be compared. Chapter IV will present the cost of contract changes caused by design deficiencies. The cost of contract changes caused by design deficiencies will be compared to the cost of

producing the design as a measure of Naval ship system design cost-effectiveness.

CHAPTER III

COST OF NAVAL SHIP SYSTEM DESIGN

Introduction

This chapter of the thesis will present the cost of ship system design for several classes of Naval ships. The cost of non-conventional design tasks will be segregated from the total ship system design costs. The cost of the conventional ship system design tasks will be adjusted to constant Fiscal Year 1976 dollars by applying a cost index based on the cost per man day of design effort.

The acquisition cost of the lead ship of each class will be presented, along with the average acquisition cost per ship for each class. The acquisition cost will be adjusted to constant Fiscal Year 1976 dollars by applying a shipbuilding cost index developed from material and labor cost indices.

The cost of the conventional ship system design tasks will be expressed as a percentage of ship acquisition cost for each ship class in order to take into account differences in ship system complexity. Ship system acquisition cost is proportional to ship system complexity, and ship system design cost is proportional to ship system complexity for constant design effectiveness. By expressing ship system

design costs in percent of ship system acquisition cost, the effect of ship system complexity is taken into account for a given type of ship. Combatant and non-combatant ships will be treated as disparate types.

Cost of Naval Ship System Design

The cost of developing a set of contract plans and specifications for a Naval ship is influenced by the efficiency of the design effort, by the complexity of the design, and by the completeness of the design [17]. Efficiency, complexity, and completeness can be further subdivided as shown in Figure 4.

The efficiency of the design effort is a measure of the amount of work done that is actually incorporated in the final plans and specifications in proportion to the total effort. Design rework due to changes in externally imposed constraints or requirements is an example of inefficient design work. This thesis will not attempt to measure the efficiency of design effort; however, some allowance will be made for obvious duplication of design effort. It is recognized that efficiency differences will introduce some data scatter, but the impact is believed to be small and within the range of error inherent in the data.

The complexity of the design is taken into account by expressing design cost in percent of acquisition cost. It has been stated that both design cost and acquisition cost are proportional to ship system complexity. At first

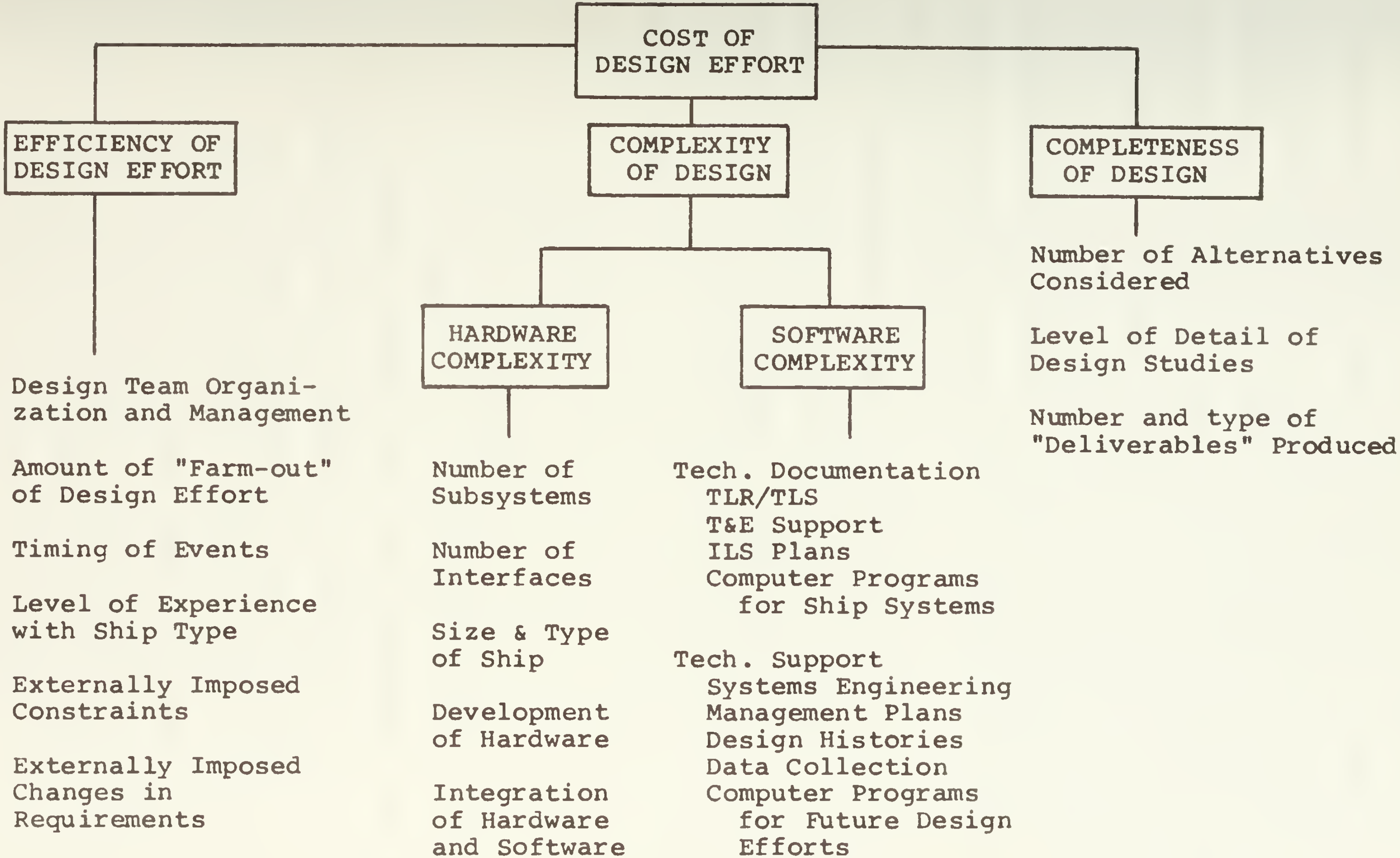

Figure 4. Factors Affecting Ship System Design Cost [17].

glance this appears to be a statement of an obvious truth, but note that nothing has been said about the factor of proportionality or the functional form relating cost to complexity. The words "taken into account" should not be interpreted to mean that the effect of ship system complexity has been eliminated. Expressing design cost in percent of acquisition cost is the author's method of making an allowance for differences in ship system complexity. Complete elimination of the effect of complexity is <u>not</u> claimed and should not be inferred.

The effects of ship system complexity would be completely eliminated by expressing design cost in percent of acquisition cost <u>if and only if both</u> design cost and acquisition cost are related to complexity by one of the functional forms:

1. Cost = αX
2. Cost = αX^X
3. Cost = αe^X or $\alpha\beta^X$

where X is complexity, α is a constant of proportionality, e is the natural log base, and β is a constant. The effects of complexity are not completely eliminated if cost and complexity are related by any other functional form, or if design cost and acquisition cost are related to complexity by different functional forms. Both design cost and acquisition cost must be related to complexity by the same functional form, and that form must be one of those listed above if the effect of ship system complexity is to be

completely eliminated by expressing design cost as a percent of acquisition cost. The functional relationship between cost and complexity is not known; therefore, the act of expressing design cost in percent of acquisition cost is merely a method of making an allowance for the effect of ship system complexity.

The effect of software complexity is eliminated by determining the cost of software, and deleting that cost. Software includes technical documentation and reports of supporting studies, planning documents, design histories, data collection, and computer programs. The elements included in software complexity are non-conventional design tasks and are, therefore, not included in the cost of the conventional elements of ship system design.

The completeness of the design is the principle factor being investigated in this thesis. The completeness of the design effort in terms of the number of alternatives considered, the level of detail of the design studies, and the number and type of products resulting from the design effort, is the principle factor affecting the cost of the conventional elements (hard-core engineering tasks) of the ship system design. The quality of the contract plans and specifications is dependent primarily on the completeness of the design effort. The cost of contract changes caused by deficiencies in the contract plans and specifications will be used to measure the effectiveness of the design effort.

The cost of developing the contract plans and specifications for different classes of Naval ships has been strongly affected by inflation. The historical cost per man-day of design labor is shown in Figure 5, and has been used to develop the labor cost index shown in Table 1. The labor cost index in Table 1 is applied to the actual "then-year" ship system design costs in order to express the design cost in constant Fiscal Year 1976 dollars.

The actual cost of developing the contract plans and specifications for twelve classes of Naval ships has been taken from references [2, 4, 29, 38, 39, 46]. The actual ship system design cost, the ship system design year, the design labor cost index, and the ship system design cost in constant Fiscal Year 1976 dollars are shown in Table 2.

The question of design efficiency is brought out again in Table 2 in the case of the FF1052 design, and the DD963 design. The FF1052 design was actually completed to the point of having a Request for Proposals (RFP) issued to prospective ship builders. The original design had provided for pressure-fired boilers. Technical difficulties were being experienced with pressure-fired boilers at that time, and a decision was made to recall the RFP and rework the design to incorporate conventional boilers. The records are not detailed enough to determine accurately the impact of this decision on the design cost, hence, the cost spread shown in Table 2.

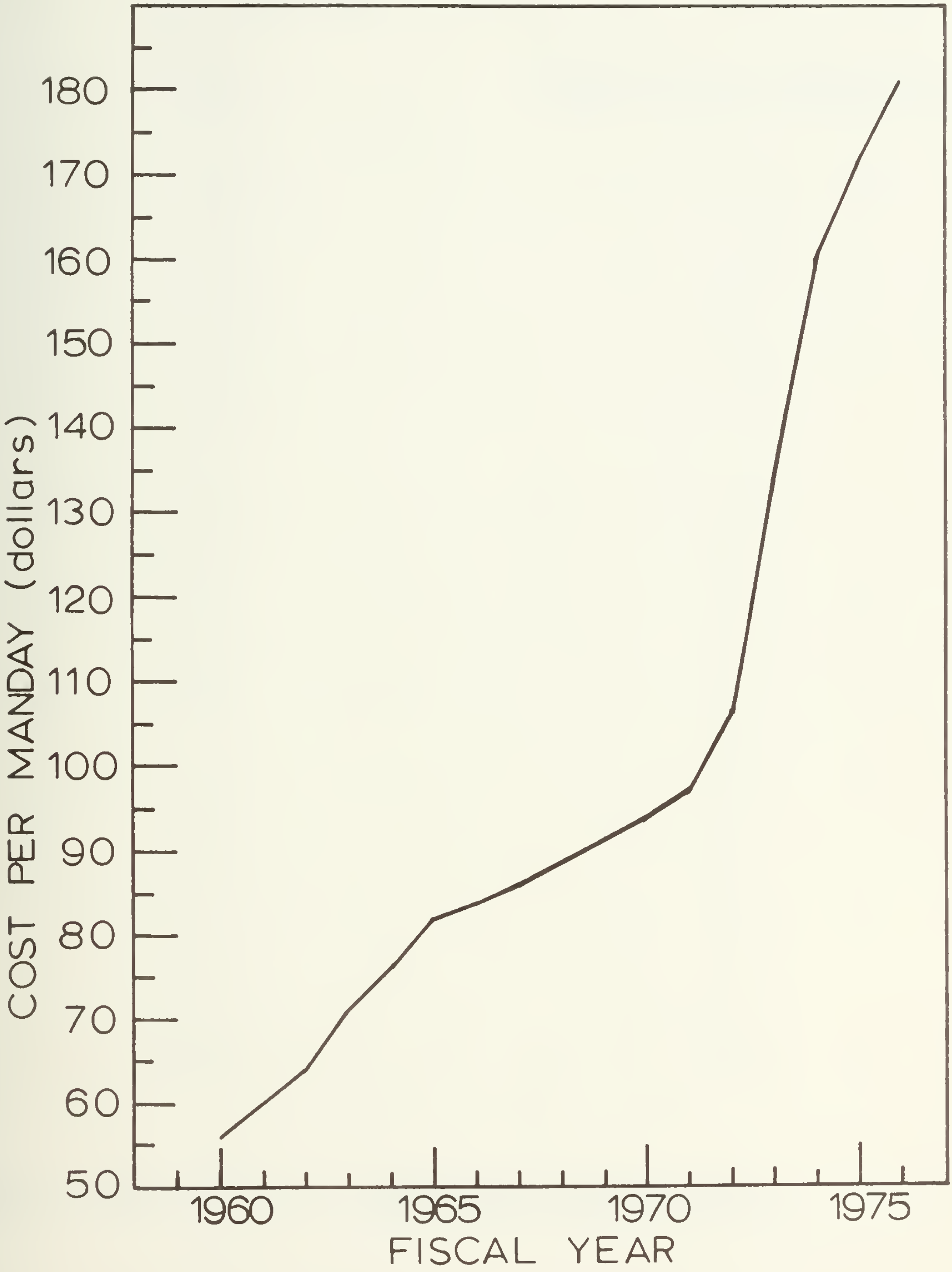

Figure 5. Historical Cost Per Man Day of Ship System Design Labor at Naval Ship Engineering Center [30, 38].

Table 1. Naval Ship Engineering Center Labor Index, 1960-1976 [30, 38].

Fiscal Year	Ship System Design Labor Index to Fiscal Year 1976
1960	3.23
1961	3.02
1962	2.83
1963	2.55
1964	2.38
1965	2.21
1966	2.15
1967	2.10
1968	2.06
1969	1.99
1970	1.93
1971	1.87
1972	1.71
1973	1.36
1974	1.13
1975	1.06
1976	1.00

$$\text{Labor Index to FY76 is } \frac{\text{FY76 cost per man-day}}{\text{Then-year cost per man-day}}$$

Table 2. Naval Ship System Design Costs in Millions of Dollars [4, 29, 38, 39, 46].

Ship Class	Ship System Design Cost $ Millions	Ship System Design Fiscal Year	Labor Index To FY76 Dollars	Ship System Design Cost in FY76 Dollars $ Millions
CG26	4.2	1961	3.0	12.6
FF1052[a]	1.0-3.0	1964	2.4	2.4-7.2
CGN36	5.5	1967	2.1	11.6
DD963[b]	22.0	1970	1.9	41.8
CGN38	20.4	1970	1.9	38.8
FFG7	9.9	1973	1.4	13.9
AO177	4.7	1975	1.1	5.2
SCS	9.5	1974	1.1	10.5
AE26	0.4	1963	2.6	1.0
LSD37	0.8	1964	2.4	1.9
LKA113	0.8	1965	2.2	1.8
AOR1	0.7	1965	2.2	1.5

Notes: a. Insufficient data for more accurate determination.

b. One contractor plus one-third of Navy review costs plus $10 million spent on system design after contract award. Source: Deputy Project Manager and former Technical Director for DD963 Acquisition Program [2].

The DD963 design was completed under the CF/CD approach. Three contractors competed during the CD phase, and the Navy reviewed the work of all three contractors. The actual amount spent by the contractors is unknown. In addition to these uncertainties, the ship system design effort continued for nearly a year after the CD phase was completed and the contract for construction was awarded. Rather than allow such obvious distortion of cost data, the author has estimated the DD963 ship system design cost. The estimate consists of the amount actually paid to one contractor (all three contractors were paid the same amount), plus one-third of the Navy review costs, plus an estimated $10 million spent on ship system design after construction contract award. These estimates are based on a conversation with the Deputy Project Manager (formerly Technical Director) of the DD963 acquisition program [2].

The remaining cost information presented in Table 2 is believed accurate within ± 10 percent for designs produced prior to 1970, and accurate within two or three percent for designs produced since 1970.

Cost of Non-Conventional Elements of Naval Ship System Design

The cost of the non-conventional elements of Naval ship system design must be separated from the total ship system design cost shown in Table 2 in order to place all the ship classes on a common design cost basis. The non-conventional elements of ship system design are:

1. Design management.

2. TLR/TLS development.

3. T&E planning.

4. ILS planning.

5. Systems Engineering.

6. Weapons and software development.

Thus, the elements of ship system design listed in the Figure 3 products column, and not listed above, are the conventional elements of Naval ship system design.

The cost of the non-conventional design elements are shown in Tables 3 through 6 for ship designs produced under the present and CF/CD approaches. These costs have been taken from references [4, 29, 39, 46]. Table 7 summarizes the non-conventional design costs. Table 7 shows that 50 to 59 percent of total ship system design cost is spent for non-conventional elements in combatant ship system design, and 28 to 30 percent of total ship system design cost is spent for non-conventional elements in non-combatant ship system design.

Cost of Conventional Elements of Naval Ship System Design

The ship system design cost remaining after deletion of the cost of non-conventional design elements is, by definition, the cost of the conventional elements of ship system design. The cost of the conventional elements of ship system design is shown in Table 8 for twelve classes of Naval ships. The design year, design labor cost index,

Table 3. CGN38 (Formerly DLGN38) Ship System Design Costs in Millions of Dollars [4, 29].

Design Element	Design Phase: Concept Formulation $ Millions	Contract Definition ($ Millions)			Element Total ($ Millions)	Element percent of Grand Total (percent)
		B_1	B_2	C		
Design Management	.15	.25	.25	.65	1.30	6.4
TLR/TLS Equivalent	.10	-	-	-	0.10	0.5
T&E	-	.07	.60	1.42	2.09	10.3
ILS	-	.25	.50	1.15	1.90	9.3
Systems Engineering	.14	.60	1.0	1.50	3.24	15.7
Weapons and Software development	-	-	-	3.38	3.38	16.6
Conventional elements	-	.78	1.90	5.70	8.38	41.2
		Grand Totals			20.39	100.0

Table 4. Patrol Frigate (FFG-7, Formerly PF-109) Ship System Design Costs in Millions of Dollars [46].

Design Element	Feasibility Studies and Conceptual Design $ Millions	Preliminary Design $ Millions	Contract Design $ Millions	Element Total $ Millions	Element Percent of Grand Total (Percent)
Design Management	Breakdown into Elements not available	0.34	1.65	1.99	20.0
TLR/TLS		0.16	-	0.16	1.6
T&E*		0.25	0.70	0.95	9.6
ILS		-	0.18	0.18	1.8
Systems Engineering		0.68	0.96	1.64	16.5
Conventional Elements		1.55	3.27	4.82	48.5
	Conceptual Design Cost Unallocated:			.19	2
		Grand Totals:		9.93	100

*Includes land based test site support.

Table 5. Sea Control Ship (SCS) Ship System Design Costs in Millions of Dollars [46].

Design Element	Feasibility Studies and Conceptual Design $ Millions	Preliminary Design $ Millions	Contract Design $ Millions	Element Percent (Contract Design Only)
Design Management	Breakdown into Elements not available	Breakdown into Elements not available	1.13	20.0
TLR/TLS			-	-
T&E			0.09	1.5
ILS			-	-
Systems Engineering			0.43	7.5
Conventional Elements			4.02	71.0
	Conceptual Design Cost Unallocated:		0.87	
	Preliminary Design Cost Unallocated:		2.98	
		Total Cost:	9.52	

Table 6. Fleet Oiler (AO177) Ship System Design Costs in Millions of Dollars [46].

Design Element	Feasibility Studies and Conceptual Design $ Millions	Preliminary Design $ Millions	Contract Design $ Millions	Element Total $ Millions	Element Percent of Grand Total (Percent)
Design Management	Breakdown into Elements not available	0.24	0.48	0.72	15.2
TLR/TLS		-	-	-	-
T&E		-	0.13	0.13	2.7
ILS		-	0.15	0.15	3.2
Systems Engineering		0.06	0.27	0.33	7.0
Conventional Elements		0.70	2.59	3.29	69.6
	Conceptual Design Cost Unallocated:			0.11	2.3
			Total Cost:	4.73	100

Table 7. Summary of the Cost of Non-Conventional Naval Ship System Design Elements as a Percentage of Total Ship System Design Cost.

Class	Design MGT. Percent	TLR/TLS Percent	T&E Percent	ILS Percent	Systems Engrng. Percent	Other Percent	Total Percent Non-Conventional
CGN38	6.4	0.5	10.3	9.3	15.7	16.6[a]	58.8
FFG-7	20.0	1.6	9.6	1.8	16.5	1.0[b]	50.5
SCS	20.0[c]	-	1.5[c]	-	7.5[c]	-	30[d]
AO177	15.2	-	2.7	3.2	7.0	.7[e]	28.8

Notes:

a. Weapons and software development.

b. One-half of unallocated conceptual design cost.

c. Contract Design Phase only.

d. Estimate based on AO177 data and SCS Contract Design data.

e. Thirty percent of unallocated conceptual design costs.

Table 8. Cost of Conventional Elements of Naval Ship System Design in Constant Fiscal Year 1976 Dollars.

Ship Class	Design* Cost[a] $ Millions	Design Fiscal Year	Design Labor Cost Index	Design* Cost in FY1976 Dollars (Millions)
CG26	4.2	1961	3.0	12.6
CGN36	5.5	1967	2.1	11.6
CGN38	8.4	1970	1.9	16.0
FF1052[b]	1.0-3.0	1964	2.4	2.4-7.2
FFG7	4.9	1973	1.4	6.9
DD963[c]	9.1	1970	1.9	17.3
LSD37	0.8	1964	2.4	1.9
LKA113	0.8	1965	2.2	1.8
AE26	0.4	1963	2.6	1.0
AOR1	0.8	1965	2.2	1.8
AO177	3.4	1975	1.1	3.7
SCS[d]	6.7	1974	1.1	7.4

Notes:
a. Design* is the conventional elements of Naval ship system design.
b. Insufficient data for more accurate determination.
c. Estimate based on CGN38 non-conventional ratio.
d. Estimated at 70 percent of total based on ratio for SCS contract design and AO177 ratios for preliminary and contract design.

and cost in constant Fiscal Year 1976 dollars are also shown in Table 8.

The cost of DD963 conventional elements of ship system design could not be determined from the records available. The cost shown in Table 8 for DD963 is an estimate based on CGN38 non-conventional cost ratio (60 percent non-conventional). The total cost of DD963 ship system design was also an estimate, hence the cost of the conventional elements of DD963 ship system design shown in Table 8 is the result of two sequential estimates and should be viewed with considerable skepticism. The cost data for the sea control ship design was not detailed enough to break conceptual and preliminary design costs into conventional and non-conventional elements. The non-conventional elements were estimated at 30 percent of the total ship system design cost, based on SCS contract design cost ratio (c.f. Table 5) and AO177 preliminary and contract design cost ratios (c.f. Table 6).

Ship acquisition cost has been strongly influenced by inflation in recent years. The inflation rate for shipbuilding is not the same as the inflation rate for design labor. Also, the period of time over which inflation acts is not the same for ship system design as for ship construction; therefore, a shipbuilding cost index separate from design labor cost index is required in order to show ship acquisition cost in constant Fiscal Year 1976 dollars.

Two types of shipbuilding cost indices are maintained by the Naval Sea Systems Command. The first type is used for calculating payments to shipbuilders under the economic escalation clause in the shipbuilding contract. This cost index is based on Bureau of Labor Statistics (BLS) cost indices for shipbuilding material and shipbuilding labor. The BLS indices are equally weighted. It is generally recognized by the Navy and contractors alike that the resulting "BLS 50-50 cost index" does not fully account for the cost increases experienced for <u>Naval</u> ship construction. The BLS indices are used for computing escalation payments primarily because the indices are maintained by a disinterested party, and not because the index is the most accurate reflection of Naval shipbuilding costs available. The BLS shipbuilding material index does not fully account for the cost increases experienced in Naval ship construction materials. Furthermore, the shipbuilder's overhead and profit are not taken into account at all in computing the BLS 50-50 index [5].

The NAVSEA cost estimating group maintains a separate shipbuilding cost index for cost estimating purposes. The index used for cost estimating purposes includes the full impact of Naval ship material costs, shipbuilder overhead and profit, and the estimated impact of economic and shipbuilding marketing factors. The index used for cost estimating purposes more accurately accounts for all the factors influencing the cost of Naval ships; unfortunately, the

index is considered sensitive and cannot be published in an unclassified paper [5]. The solution to this dilemma is a compromise cost index based on the NAVSEA material cost index and the BLS labor index, equally weighted. The resulting cost index, shown in Table 9, is better than the BLS 50-50 index, but not nearly as good as the NAVSEA cost estimating index.

Ship acquisition cost extracted from [40] is shown in Table 10 for twelve classes of Naval ships, along with the shipbuilding year, and the ship acquisition cost in constant Fiscal Year 1976 dollars. The data in Table 10 show that the cost index in Table 9 does not fully account for inflation. Compare the cost of AOR-1 class ships in FY1976 dollars ($74M) to the cost of AO177 class ships in FY1976 dollars ($98M). The AOR-1 class ships are larger and more complex than AO177 class ships and certainly cannot be acquired for less than AO177 class ships in 1976. Also, CG26 class ships, shown at a cost of $140M in Table 10, cannot be built for less than DD963 class ships, shown at a cost of $179M in Table 10. It is apparent that the cost index being used does not fully account for inflation; however, it is the best information publishable and will be used throughout this thesis. It will be shown that the results obtained in Chapter IV are sensitive to errors in the shipbuilding cost index, hence, the reader should keep in mind the shortcomings of the index being used.

Table 9. Shipbuilding Cost Index to Convert To Fiscal Year 1976 Dollars Based on NAVSEA Material Index and Bureau of Labor Statistics Labor Index, Weighted Equally [5].

Shipbuilding Fiscal Year	NAVSEA Material Index	BLS Labor Index	Shipbuilding Cost Index to FY76
1964	3.18	2.01	2.59
1965	3.05	1.97	2.51
1966	2.90	1.92	2.41
1967	2.75	1.83	2.29
1968	2.61	1.80	2.21
1969	2.46	1.66	2.06
1970	2.28	1.59	1.94
1971	2.09	1.53	1.81
1972	1.86	1.45	1.66
1973	1.62	1.38	1.50
1974	1.41	1.25	1.33
1975	1.20	1.13	1.17
1976	1.00	1.00	1.00

Table 10. Acquisition Cost of Naval Ships in Constant Fiscal Year 1976 Dollars [40].

Ship Class	Ships in Class	Lead Ship Cost $Millions	Average Ship Cost $Millions	Lead Ship Fiscal Year	Average Ship Fiscal Year	FY1976 Lead Ship Cost $Millions	FY1976 Average Ship Cost $Millions
CG26	9	65.9	55.6	1964	1965	171	140
CGN36	2	206.2	196.6	1972	1972	342	326
CGN38[a]	3	258.4	244.2	1974	1974	343	325
FF1052	46	58.5	26.4	1967	1970	134	52
FFG7[a]	50	248.6	109.0	1975	1976	291	109
DD963[a]	30	107.4	92.4	1970	1970	209	179
LSD37	4	29.2	30.4	1968	1969	64	63
LKA113	4	31.8	27.4	1968	1969	70	56
AE26	4	34.9	35.5	1967	1967	80	81
AOR1	6	41.2	38.4	1968	1970	92	74
AO177[a]	6	141.4	98.0	1976	1976	141	98
SCS[b]	8	172.0	117.0	1973	1973	257	175

Notes: a. Program Estimates.

b. Design to cost goal.

The cost of ship system design, and the ship acquisition cost have been presented, and correction has been made for inflationary effects. The cost of the conventional elements of ship system design is shown as a percent of lead ship acquisition cost and average ship acquisition cost in Table 11. The historical trend of the cost of conventional elements of ship system design is shown in Figure 6 through 11.

The Sea Control Ship (SCS) is classified by the Navy as a combatant ship. The SCS has a combatant mission; however, the ship is more similar to a non-combatant ship from the viewpoint of the ship system designer. This author has classified the SCS as a non-combatant ship for the purpose of ship system design based on the austerity and simplicity of the SCS platform, compared to frigates, cruisers, destroyers and attack aircraft carriers.

In general, the cost of the conventional elements of ship system design has been smaller for non-combatant ships than for combatant ships. This is true both in absolute dollars and in percent of acquisition cost.

Examination of Figures 6 through 11 reveals some interesting historical trends. Figures 6 and 7 show that the total cost of ship system design, in percent of acquisition cost, has been increasing. The trend in Figure 6 is very clear in the case of non-combatant ships. Figure 7 displays considerable variation in the total cost of combatant ship system design, but the trend is clearly increasing.

Table 11. Cost of Conventional Elements of Naval Ship System Design as a Percentage of Ship Acquisition Cost.

Ship Class	Design* Percent of Lead Ship Acq. Cost	Design* Percent of Average Ship Acq. Cost
CG26	7.4	9.0
CGN36	3.4	3.6
CGN38	4.7	4.9
FF1052	1.8-5.4	4.6-13.8
FFG7	2.4	6.3
DD963	8.3	9.7
LSD37	3.0	3.0
LKA113	2.6	3.2
AE26	1.2	1.2
AOR1	2.0	2.4
AO177	2.6	3.8
SCS	2.9	4.3

Notes: Design* is the Conventional elements of Naval ship system design.

All costs converted to 1976 Dollars before expressing design* cost in percent of ship acquisition cost.

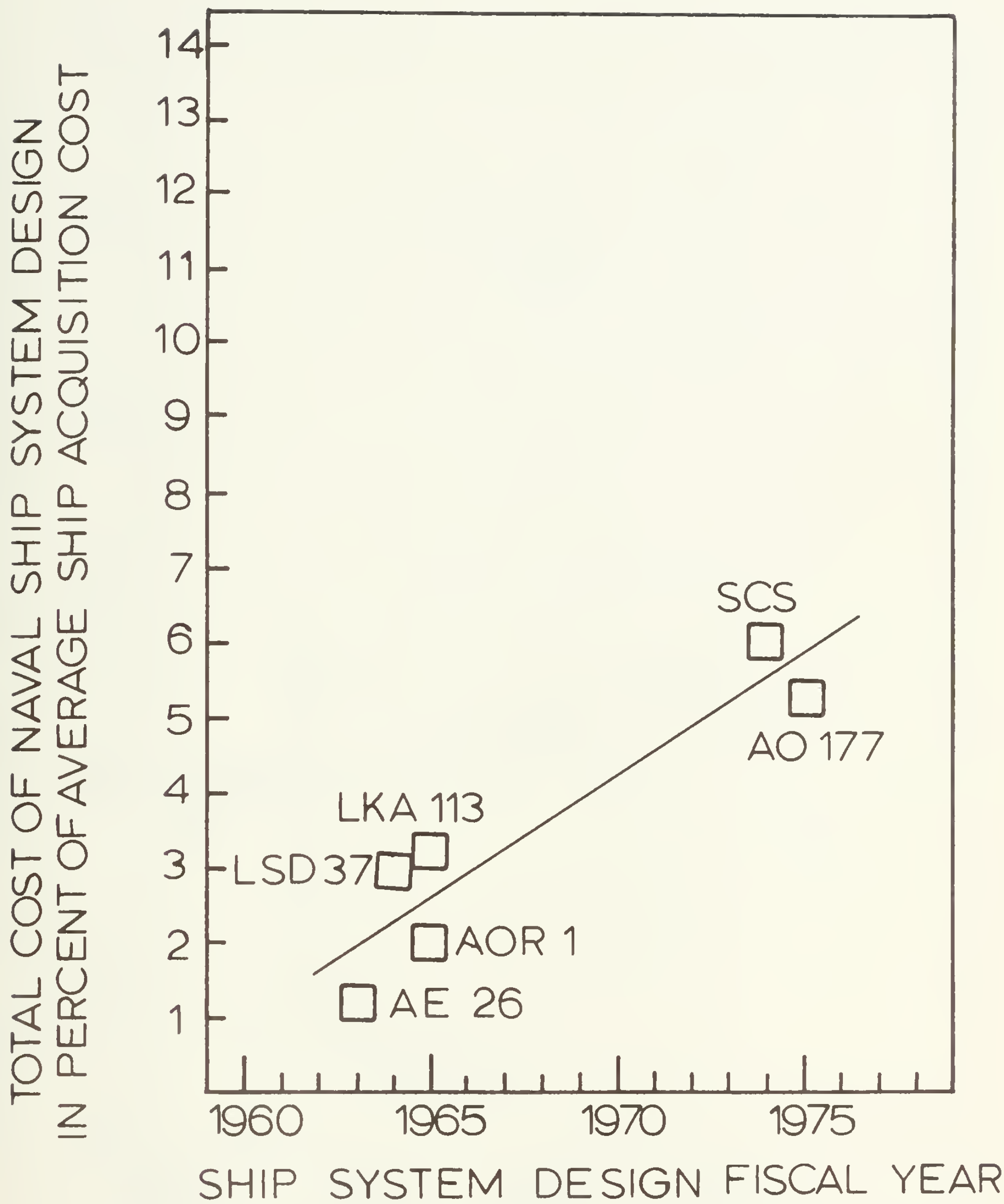

Figure 6. Historical Trend of Total Cost of Naval Ship System Design in Percent of Average Ship Acquisition Cost for Non-Combatant Ships.

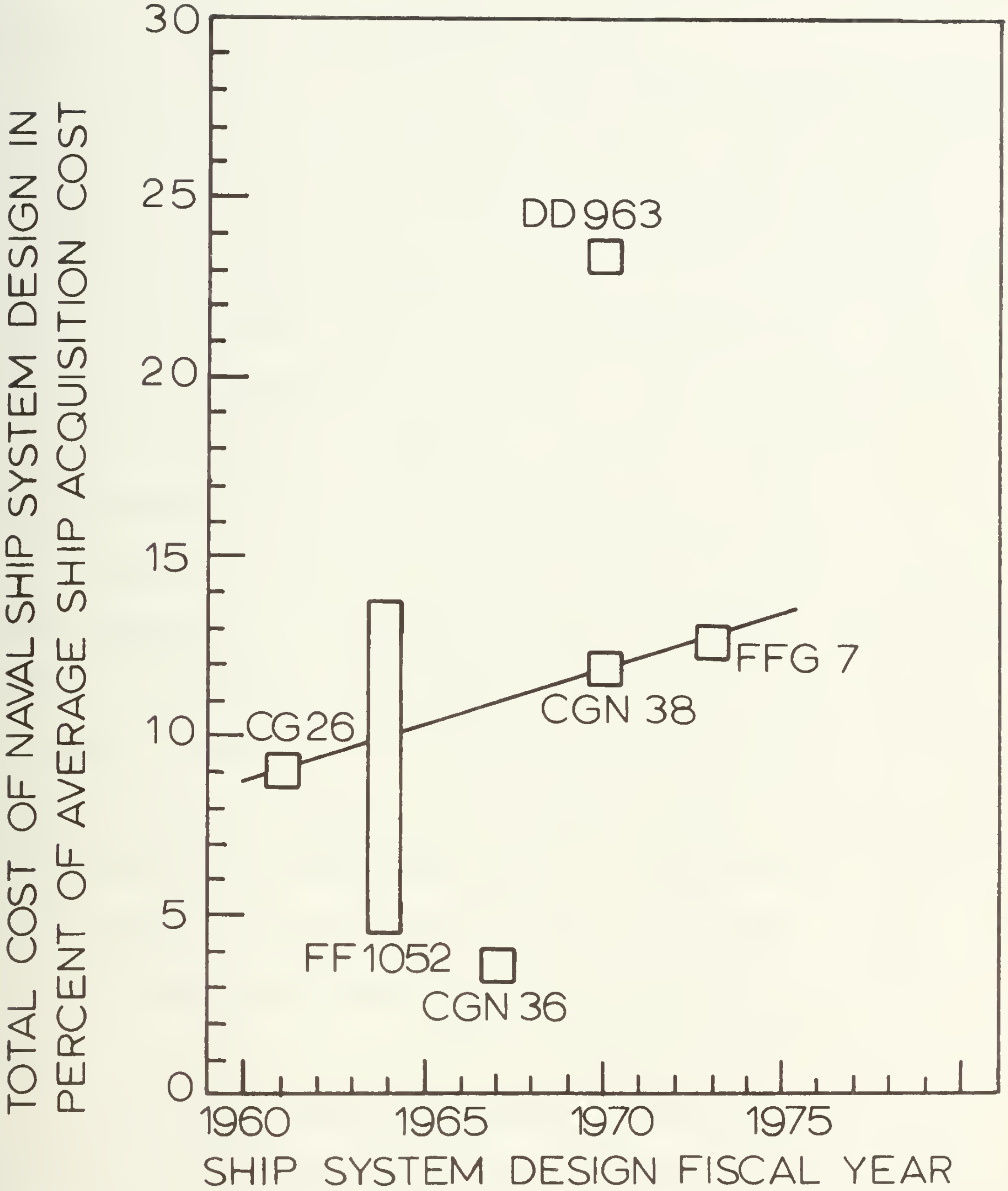

Figure 7. Historical Trend of Total Cost of Naval Ship System Design in Percent of Average Ship Acquisition Cost for Combatant Ships.

The data point for DD963 shown in Figure 7 has been ignored in drawing the trend line due to the sequential estimating procedure used to obtain the data point.

The total cost of ship system design shows an increasing percentage of ship acquisition cost. Figures 8 and 9 show that the cost of the conventional elements of ship system design also displays a trend of increasing percentage of ship acquisition costs for non-combatant ships. The trend is more pronounced in Figure 9, where ship system design cost is shown in percent of average ship acquisition cost as opposed to lead ship acquisition cost.

Figures 10 and 11 show that the cost of the conventional elements of ship system design displays considerable scatter in percentage of combatant ship acquisition cost. It should be noted that the FFG7 data point shown in Figure 11 is an estimate based on a 50 ship program. Recent actions by Congressional Committees indicate that the FFG program may be cut severely, which would result in a higher average ship cost and lower percentage spent for hard-core engineering tasks.

The trends shown in Figures 6 through 9 are in the direction recommended by the SCN Pricing and Cost Control Study and by the Navy Marine Acquisition Review Committee. The scatter shown in Figures 10 and 11 do not display any clear trend.

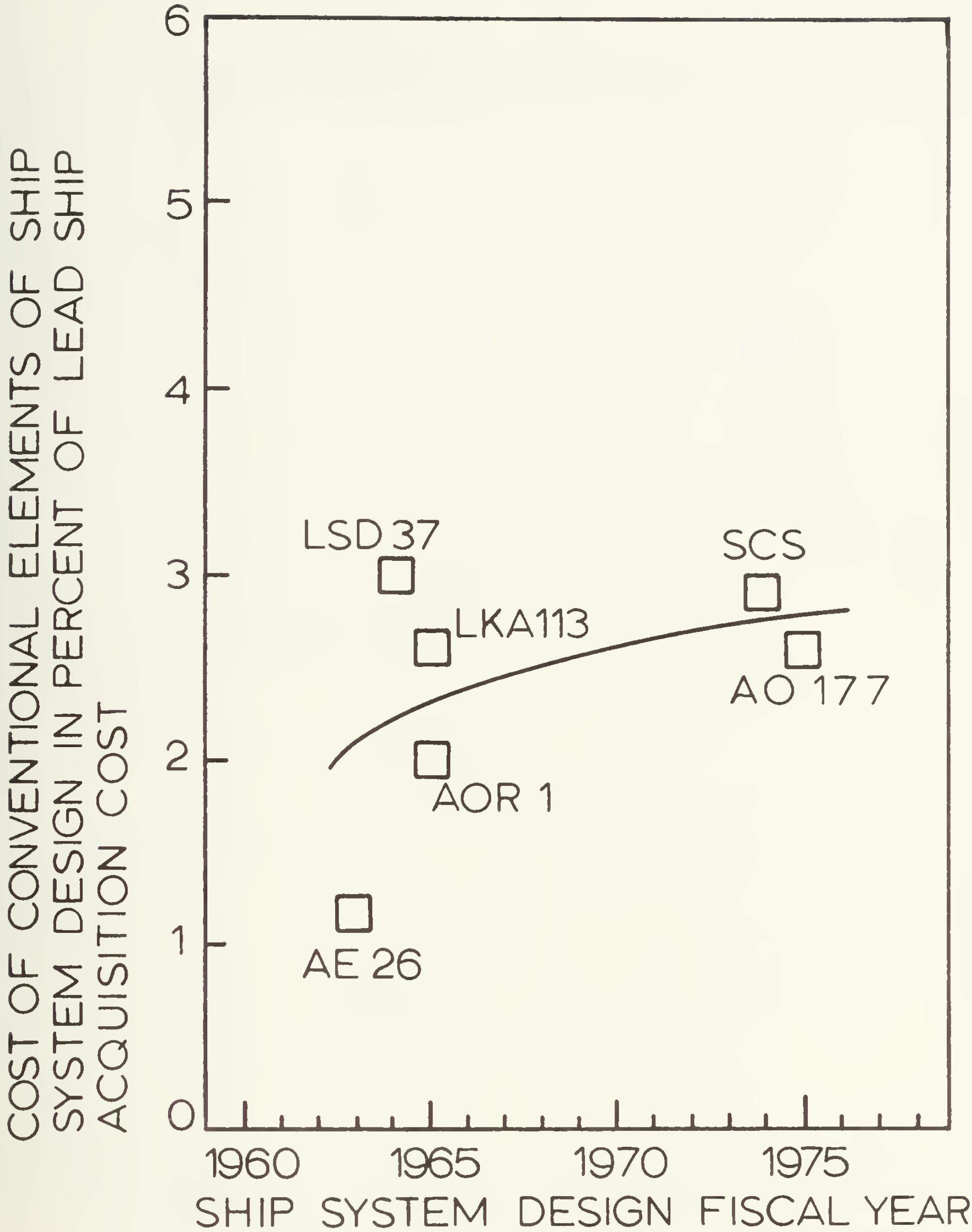

Figure 8. Historical Trend of Cost of Conventional Elements of Naval Ship System Design in Percent of Lead Ship Acquisition Cost for Non-Combatant Ships.

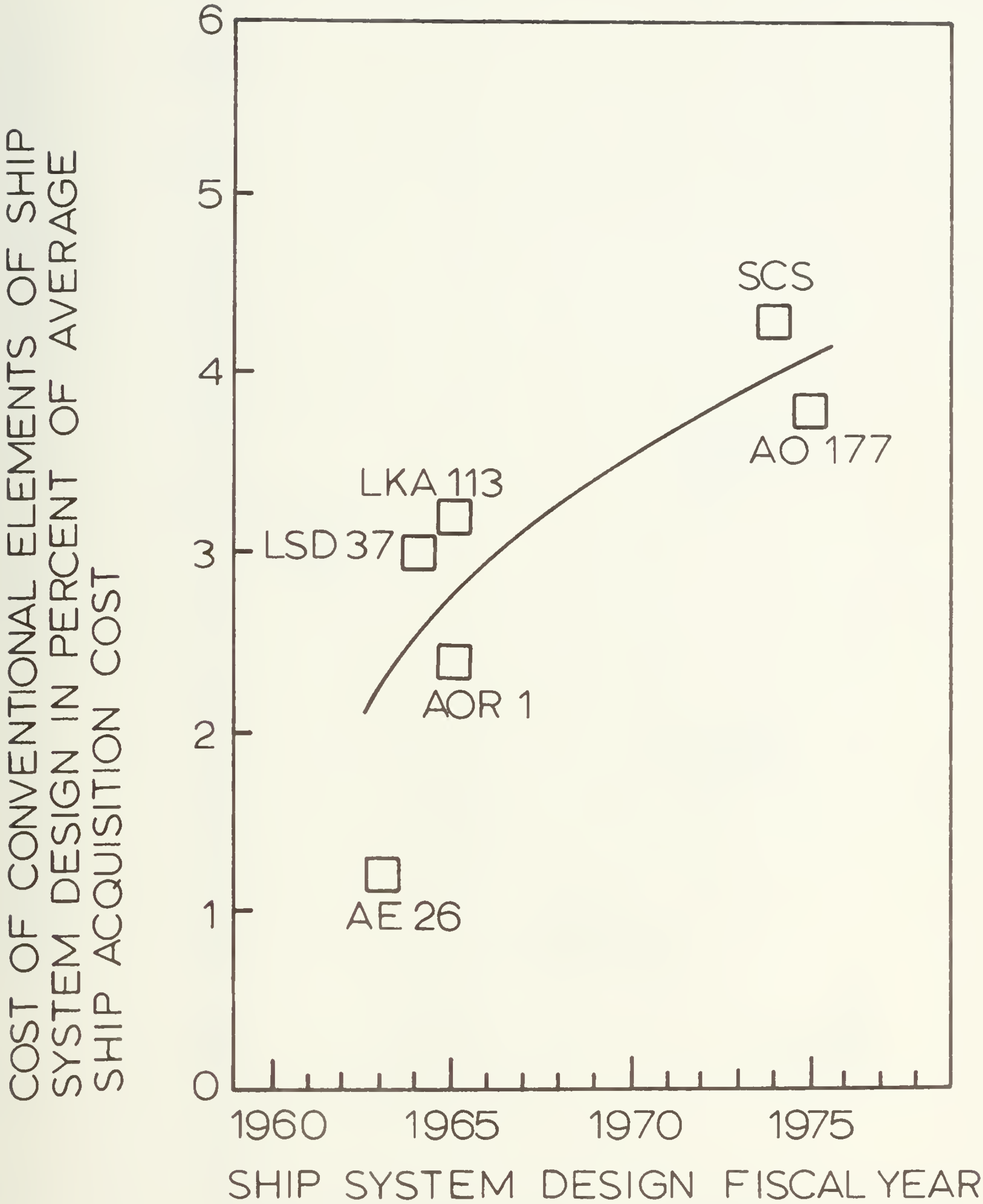

Figure 9. Historical Trend of Cost of Conventional Elements of Naval Ship System Design in Percent of Average Ship Acquisition Cost for Non-Combatant Ships.

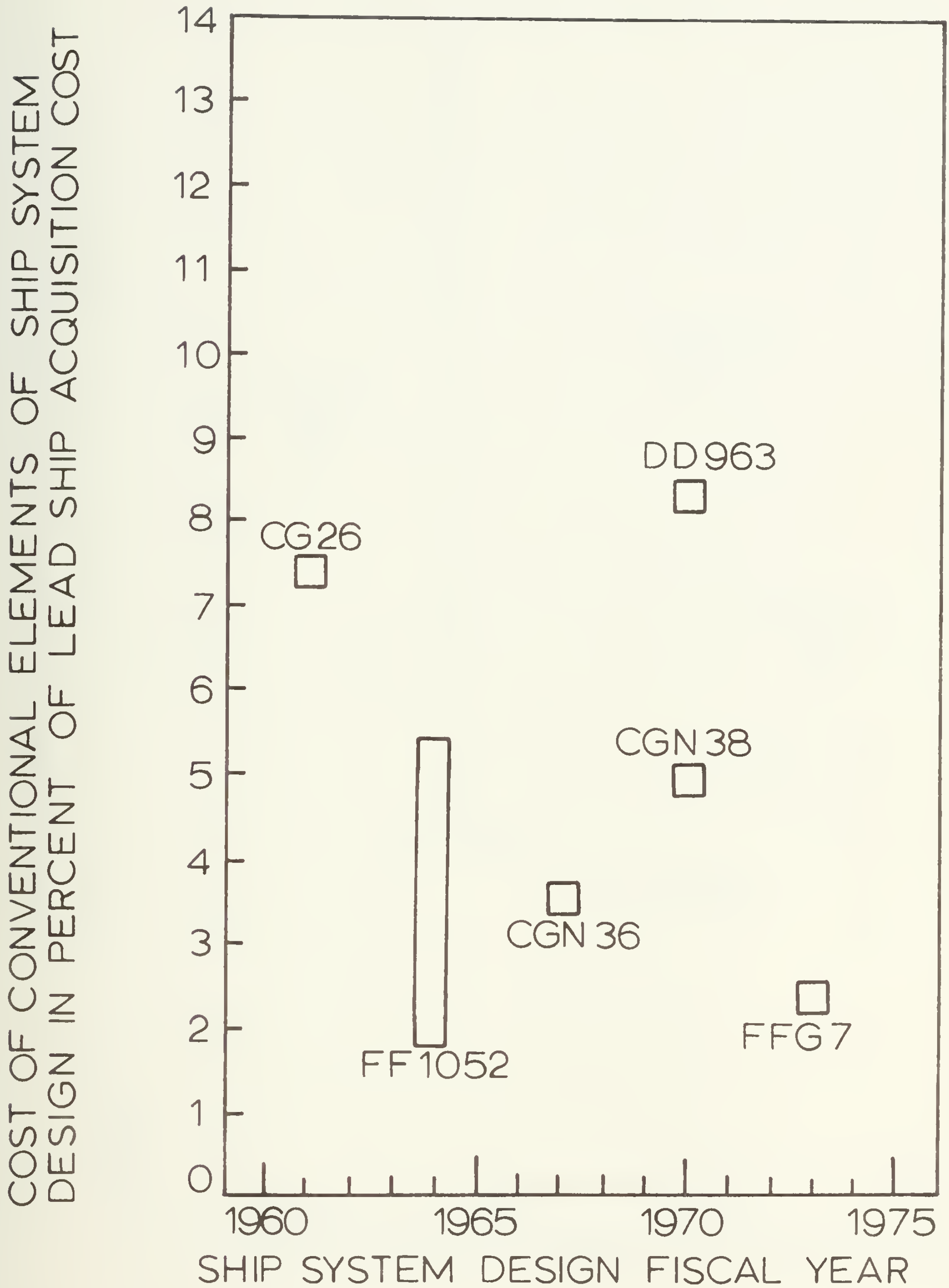

Figure 10. Historical Cost of Conventional Elements of Naval Ship System Design in Percent of Lead Ship Acquisition Cost for Combatant Ships.

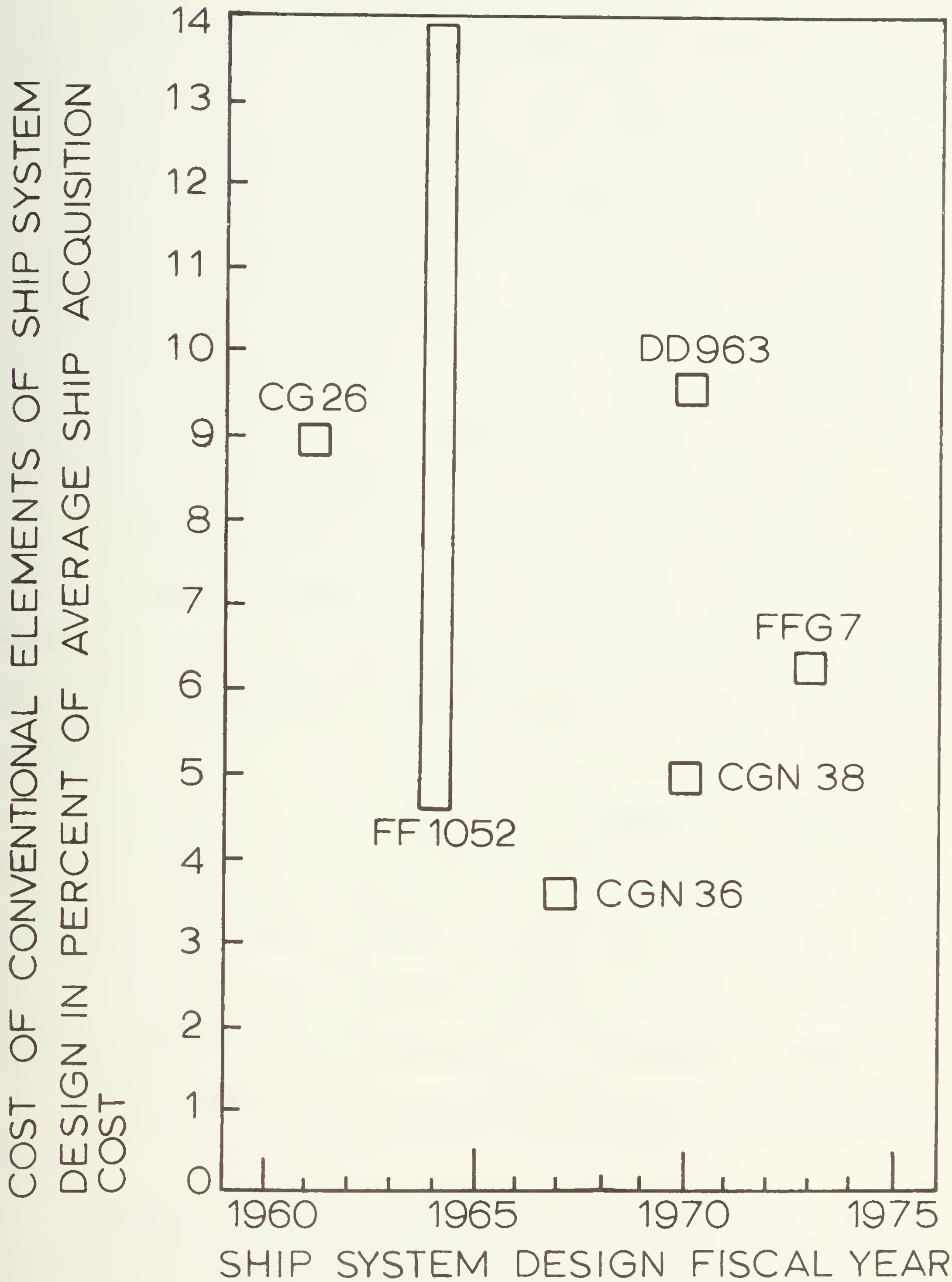

Figure 11. Historical Cost of Conventional Elements of Naval Ship System Design in Percent of Average Ship Acquisition Cost for Combatant Ships.

Summary and Conclusions

The cost of ship system design has been presented for twelve classes of Naval ships. The cost of non-conventional design tasks has been separated, and the remaining cost (cost of conventional design tasks) has been adjusted for inflation. Non-conventional design tasks such as design management, TLR/TLS development, T&E, and ILS planning, systems engineering, and weapons and software development amount to 50 to 59 percent of the total design cost for combatant ships and 28 to 30 percent for non-combatant ships.

The ship acquisition cost was presented for the same twelve classes of Naval ships. The acquisition cost was adjusted for inflationary effects. The shipbuilding cost index used is imperfect but is based on the best data publishable.

The cost of the conventional elements of ship system design was expressed in percent of ship acquisition cost. The historical trends reveal an increasing percentage of ship acquisition cost is being expended on the conventional elements of ship system design for non-combatant ships. The data scatter does not reveal any clear trend for combatant ships.

Chapter IV will present the cost of contract changes caused by deficiencies in the contract plans and specifications. The cost of changes will be adjusted for inflation and expressed in percent of ship acquisition cost. The cost of changes caused by design deficiencies will be compared to

the cost of producing the design as a measure of ship system design cost-effectiveness.

the cost of producing the design as a measure of ship system design cost-effectiveness.

CHAPTER IV

EFFECTIVENESS OF NAVAL SHIP SYSTEM DESIGN

Introduction

This chapter of the thesis will present the cost of contract changes caused by ship system design deficiencies. The cost of contract changes will be adjusted for inflationary effects by applying the shipbuilding cost index from the midpoint of ship construction to mid-1976.

The cost of changes caused by design deficiencies, in constant fiscal year 1976 dollars, will then be expressed in percent of lead ship and average ship acquisition cost in order to take into account differences in ship system complexity. The cost of changes caused by ship system design deficiencies is proportional to ship system complexity for a constant level of design effectiveness, and ship system acquisition cost is also proportional to ship system complexity. The effect of ship system complexity is taken into account by expressing the cost of changes caused by design deficiencies in percent of ship system acquisition cost. Combatant and non-combatant ships will be treated as disparate types.

Measure of Naval Ship System Design Effectiveness

The conventional elements of Naval ship system design defined in Chapter II are hard-core engineering tasks. The conventional elements of design are responsible for the technical accuracy of the contract plans and specifications. The non-conventional elements do not contribute toward improving the technical accuracy, consistency, completeness, or clarity of the contract plans and specifications; however, the non-conventional elements may have a very large payoff in terms of ship system performance, reduced life cycle costs, and smoother introduction of the new ship into the fleet. The effectiveness of non-conventional elements of Naval ship system design will not be determined in this thesis.

The effectiveness of the effort expended on the conventional elements of Naval ship system design will be measured by the cost of contract changes caused by deficiencies in the contract plans and specifications. The recommendations of the SCN Pricing and Cost Control Study, the findings of Meiners, and the NMARC recommendation to continue increasing the scope of effort going into preparation of contract plans and specifications imply that more design effort should result in fewer and less costly changes caused by deficiencies in the contract plans and specifications. It is primarily due to these recommendations that the author has chosen the cost of contract changes caused by design deficiencies as a measure of ship system design

effectiveness, rather than some unquantifiable attribute such as performance or a less meaningful measure such as number of pages of specifications, number of plans, or number of mistakes in the plans and specifications.

Chapter III presented data on the level of effort expended on the conventional elements (hard-core engineering tasks) in preparation of contract plans and specifications. It was shown that the historical level of effort has varied considerably among Naval ship system designs. It was further shown that, although the total level of design effort has been increasing, the level of effort expended on hard-core engineering tasks has been too erratic to draw any conclusion for combatant ships. This chapter will show that the effect of variations in the level of hard-core engineering effort is clearly evident in the amount of money spent on contract changes caused by deficiencies in the contract plans and specifications.

Causes of Contract Changes

Deficiencies in contract plans and specifications is only one cause of contract changes, there are many other causes. Meiners reported that the more significant causes, in order of impact on cost growth, include:

1. Change in operational requirements.
2. Incomplete plans and specifications at time of contract award.

3. Changes in program direction/funding other than change in quantity.
4. Change to incorporate newly achieved state-of-the-art.
5. Research and development performed in production contracts.

This author has broadened the definition of cause number two above. Viewed from the standpoint of the ship system designer, the contract plans and specifications are deficient if they are incomplete, inconsistent, in error, unclear, insufficient in level of detail of system/subsystem definition, insufficient in level of detail of system/subsystem interface definition, or inadequate in terms of weight and space allocation for detail design development. Any contract change caused by one or more of these conditions is classified as a "Design Deficiency" in this thesis.

Implementation of Contract Changes

Contract changes are implemented by a Headquarters Modification Request (HMR) or by a Field Modification Request (FMR). Changes implemented by HMR tend to be fewer in number, but more expensive than changes implemented by FMR. A change caused by a design deficiency may be implemented by either HMR or FMR, depending on the nature and cost of the change.

Method of Collecting Design Deficiency Data

The HMR and FMR are contractual documents. The cause underlying the HMR or FMR is not always indicated by the contractual document, and classification of the HMR/FMR on the basis of title alone is often misleading and inaccurate. The technical documentation supporting the HMR/FMR must be reviewed in order to accurately classify the change according to the underlying cause. Fortunately, it is a general practice to file each HMR/FMR, supporting technical documentation, and pertinent correspondence together in a single file folder. Had this not been the case, the research effort would have been beyond the scope of a thesis.

The method of collecting design deficiency data consisted of reviewing the file folder for each HMR/FMR and classifying the underlying cause on the basis of information contained in that folder.

The time required for the research effort was reduced significantly by several techniques. These included the following:

1. Any HMR/FMR that resulted in no change in price was ignored.
2. Certain types of changes occur repeatedly, and can be identified on the basis of title alone. An example is "Repair GFE."
3. The Engineering Change Proposal that initiated the change was frequently included in the file folder, and contained the

"Reason for Change" in block 17 of the standard form used for Engineering Change Proposals.

These three techniques allowed most HMR/FMR changes to be classified by underlying cause in a matter of a few minutes for each change. However, a significant number of changes required additional research, and some required the aid of personnel assigned to the ship acquisition project staff, before the cause of the change could be determined.

With the HMR/FMR classified by underlying cause, the next step was to establish the change in price. When the change had resulted in a Priced Supplemental Agreement, the change in price was certain. In some cases the HMR/FMR had been issued as a unilateral change order by the Navy, with the price to be negotiated later "pursuant to the changes clause" of the contract. In these cases the Navy estimated cost of the change was used; the actual change in price is uncertain, but the estimate is based on the best information available. Changes resulting in a reduction in price were included in the data collected. A reduced price change reduces the cost of changes caused by design deficiencies. The cost of shipbuilder claims against the Navy have not been included in the data, with one exception.

The shipbuilder generally will file a claim against the Navy if the shipbuilder's profit is in jeopardy, and will use every means at his disposal to improve his profit

position. The more common elements of a claim against the Navy include:

1. Disruption and delay due to:
    a. Late or defective GFE.
    b. Late or defective GFI, other than contract plans and specifications.
    c. Technical direction by personnel other than the contracting officer (constructive change).
2. Deficient contract plans and specifications.
3. Any decision or act, or lack of a decision or act, on the part of the Navy that has the effect of increasing the shipbuilder's costs.

Claims against the Navy are usually settled by negotiation between shipbuilder and Navy attorneys. The settlement is frequently the result of an agreement between attorneys and is based more on the practical aspects of arranging a quick and equitable settlement than on the technical merits of each separate issue. In fact, the final agreement frequently does not describe the technical issues, nor does it allocate an amount to each issue. In general, determination of the exact amount of a claim allocable to a specific deficiency in contract plans and specifications is impossible. Therefore, the cost of claims that are the result of deficiencies in contract plans and specifications is not included in the data with the following exception.

The AE26 class contract plans and specifications contained a very serious engineering error in that the specified scantlings were insufficient. The Navy issued a unilateral mandatory change order to correct the deficiency. The shipbuilder refused to negotiate a price for that change, and ultimately included it as an element of a claim against the Navy. In this case the scantling deficiency change was settled as a separate claim item, and the cost allocable to that change was clear. This change was a glaring example of deficient design; the cost was clearly known, and the cost was so large (90 percent of total cost of design deficiency changes for the AE26) that it would be misleading to not include the claim cost in this case. It is an exception that the author feels necessary in order to present the true impact of deficient design in the AE26 class acquisition program. It is admittedly inconsistent to include the cost of only this claim, but the truth would suffer more if the cost of this particular claim were not included in determining the cost of design deficiencies for the AE26 class.

The effect of inflation was taken into account by applying the shipbuilding cost index from the midpoint of ship construction to mid-1976. The effect of inflation had to be taken into account since the period of time over which inflation acts and the rate of inflation for change costs is different from the time period and inflation rate for ship system design costs.

Results

The data collected for the lead ship of each class are shown in Table 12. The total cost of changes caused by design deficiencies is shown, along with the fiscal year of the midpoint of construction, the shipbuilding cost index, and the cost of design deficiency changes in constant Fiscal Year 1976 dollars. The cost of lead ship changes in percent of lead ship acquisition cost is also shown.

The cost data for the CG26 class lead ship is based on incomplete data. The FMR records for this class were complete; however, 32 out of 281 file folders were missing from the HMR records. A total of 281 HMR changes were made; the file folders for HMR 169 through HMR 200 could not be located. The cost of changes caused by design deficiencies shown for CG26 must, therefore, be considered low. The 32 missing file folders constitute 11 percent of the changes made by HMR.

The costs shown in Table 12 for CGN36 are considered accurate and complete. The CGN38 data are accurate but not complete simply because the ship has not been delivered to the Navy; however, the ship construction is nearly complete; and the author considers it unlikely that any further changes will be made due to design deficiencies.

The DD963 data are accurate and complete for the lead ship. It should be noted the ship system design for DD963 was completed in June, 1971, nearly one year after award of the TPP contract for 30 ships. Fifteen significant changes

Table 12. Cost of Lead Ship Contract Changes caused by Deficiencies in Contract Plans and Specifications [6-14, 20-28].

Ship Class	Cost of Lead Ship Changes* $Millions	Lead Ship Fiscal Year	Shipbuilding Cost Index	Cost of Lead Ship Changes* in FY76 Dollars $Millions	Lead Ship Changes* in Percent of Lead Ship Acquisition Cost
CG26	0.47	1964	2.59	1.22	0.71
CGN36	3.30	1972	1.66	5.5	1.61
CGN38	2.80	1974	1.33	3.7	1.14
DD963	0.14	1970	1.94	0.27	0.13
LSD37	0.16	1968	2.21	0.35	0.55
LKA113	0.23	1968	2.21	0.51	0.71
AE26	1.11	1967	2.29	2.54	3.18
AOR1	0.50	1968	2.06	1.0	1.12
FFG7	7.66	1975	1.17	9.0	3.08

Changes* are contract changes caused by deficiencies in contract plans and specifications.

were made during the year between contract award and completion of ship system design, including six changes resulting in a significant decrease in ship cost. The data shown in Table 12 do not include the cost (increased or decreased) of any changes made prior to June, 1971, because the ship system design was not considered complete until June, 1971.

The data shown in Table 12 for LSD37, LKA113, AE26, and AOR1 are reasonably complete and accurate. Note that 90 percent ($1.0M) of the cost of lead ship changes for AE26 is due to a claim caused by a mandatory change order issued to correct deficient scantlings.

The data for FFG7 are preliminary and should be considered a lower bound since the ship will not be delivered until mid-1977. Significant growth in the cost of changes caused by design deficiencies is not anticipated; however, some additional growth will undoubtedly occur.

The change records for the FF1052 acquisition program were only partially available. The data that could be obtained was so distorted by special deferred work cost accounts, claims, and multiple shipbuilders, that the author was unable to use it; hence, the FF1052 acquisition program is not included in this chapter. It is estimated that a minimum of six man-months of effort would be required to collect the FF1052 data, and sort out all the distorting influences [47].

The data in Table 12 together with the data in Table 11 are plotted in Figure 12. The data points are boxed with

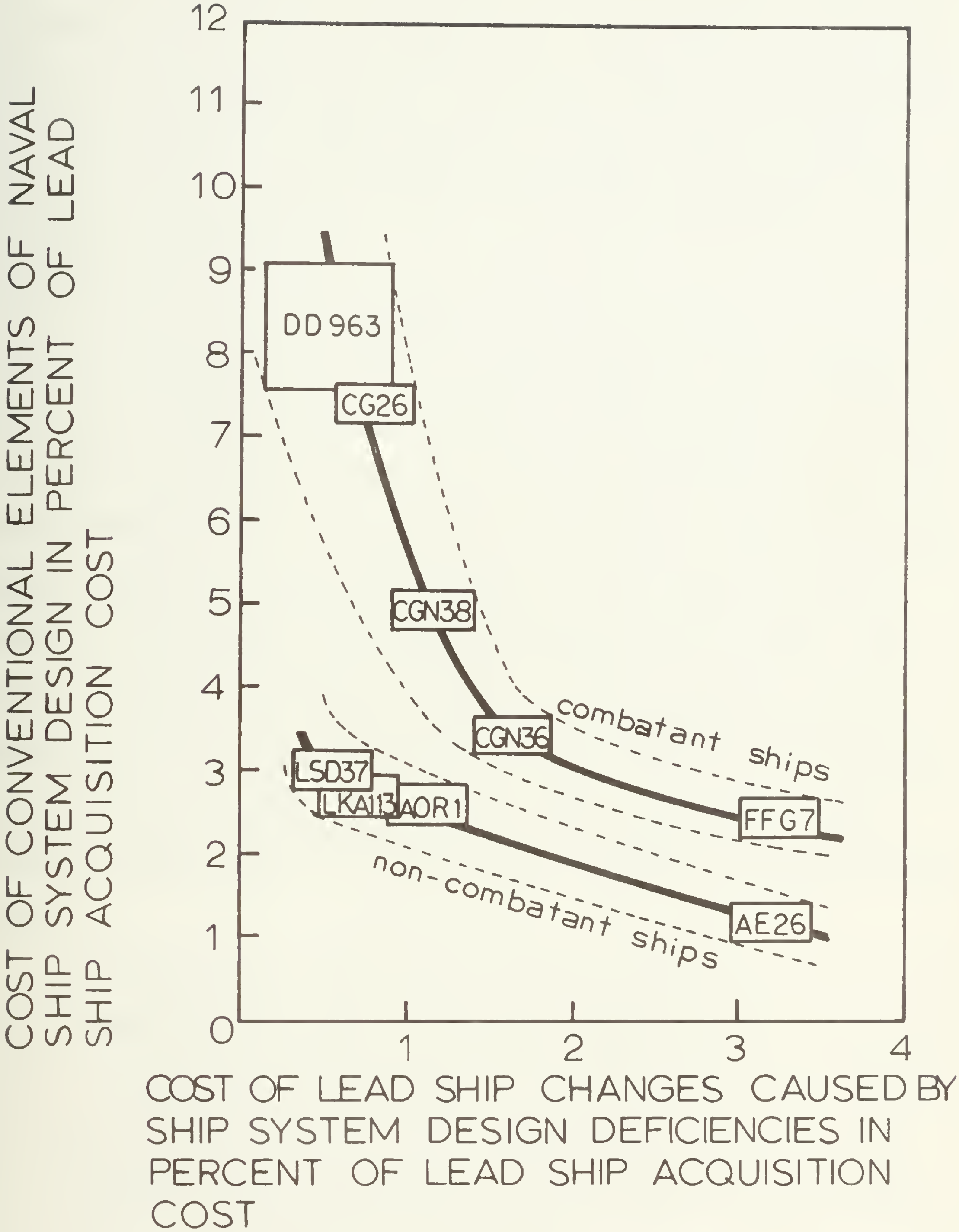

Figure 12. Naval Ship System Design Cost-Effectiveness Function for Lead Ship or Single Ship Buy.

the author's estimate of probable error in repeatability of the data by a different researcher. The boxed data points show the cost effectiveness function, along with the probable error band in a manner similar to the design "lanes" used by a ship system designer for tentative selection of hull form coefficients.

It is clear from Figure 12 that increasing the level of effort expended on hard-core engineering tasks reduces the cost of changes caused by design deficiencies; however, the payoff of increased effort exhibits decreasing marginal returns as the level of effort is increased. The payoff for combatant ships decreases rapidly as the level of effort exceeds 3 1/2 percent of lead ship acquisition cost. The payoff of increased design effort is approximately a constant ratio of 1.5 units reduction in changes cost for each additional unit spent on hard-core engineering at levels of effort below about 3 1/2 percent of lead ship acquisition cost.

It should be noted that the very small cost of changes due to design deficiencies shown for DD963 may be the result of the TPP contracting strategy rather than due to extreme excellence of the design. The shipbuilder is responsible for correcting design deficiencies at no cost to the Navy, except in cases of dispute over the existence of a design deficiency. In some cases, the Navy may judge the design deficient, and want a design change, while the shipbuilder may judge the design to be fully adequate. In these cases

the Navy must pay to have a design change implemented. The error box for the DD963 has been extended to the right to reflect the uncertainty about this point. Also, recall that the DD963 design cost is based on estimated data.

The payoff of increased design effort is also apparent for non-combatant ships, but the level at which the payoff starts decreasing is not as clear simply because no data points exist at high enough levels of design effort. The payoff must decrease as the level of effort is increased above three percent of lead ship acquisition cost, but the exact break-point in the curve is not clear. The payoff appears to be approximately a constant ratio of 1.5 units reduction in changes cost for each additional unit spent on hard-core engineering at levels of effort below about 2 1/4 percent of lead ship acquisition cost.

The optimum level of design effort is at the point where the slope of the cost effectiveness function is minus one. It is at this point that the last unit spent on design reduces the cost of changes caused by design deficiencies by exactly one unit. Spending more on design will result in a reduction of less than one unit in design deficiency changes cost for each unit spent on design. Spending less on design will result in an increase of more than one unit in design deficiency changes cost for each unit saved in design costs. "Design" means the conventional elements of Naval ship system design in this discussion.

The optimum level of design effort appears to occur at 3 1/2 percent (+ 1 percent, - 1/2 percent) of lead ship acquisition cost for combatant ships, and at 2.7 percent (± 1/2 percent) of lead ship acquisition cost for non-combatant ships. Note that DD963, CG26, CGN38, and LSD37 data points show that more than the optimum amount of effort was expended on these designs, indicating that sufficient design capacity exists to support an optimum level of effort.

The cost-effectiveness function shown in Figure 12 applies only to the lead ship of a lead-follow acquisition strategy, or to a single ship buy. The fixed costs of an acquisition program, such as design, land based test sites, etc., can be amortized over a larger number of ships if several ships are acquired on one contract. Also, the time delay involved in a true lead-follow acquisition strategy may be unacceptable in some acquisition programs. The exact size of buy required to apply the lead-follow approach is a matter of uncertainty, but most Ship Acquisition Project Managers agree that a minimum of 10 to 20 ships are needed in order to take best advantage of the lead-follow approach. Ship acquisition programs smaller than 10 to 20 ships would very likely follow the more traditional approach of buying all ships on one multiship contract. The question of "How much design is enough" remains to be answered for a multi-ship acquisition program.

The cost of design is shown in percent of average ship acquisition cost in Table 11. The average cost <u>per ship</u> of

changes caused by design deficiencies is shown in Table 13. Previous comments regarding the quality of the data still apply.

The difference between Table 12 and Table 13 is not large, but is significant in that fixed acquisition costs are amortized over all ships in the class on an equal basis. Also, the cost of changes in later ships in the class is generally less simply because the changes are made at an earlier stage in ship construction.

The data in Table 13 is combined with that in Table 11 and plotted in Figure 13, resulting in a Naval ship system design cost-effectiveness function for multiship programs on a per ship basis. It should be noted that only those ships in the initial contract award for each class have been included in the data for Table 13 and Figure 13. When additional ships of the same class are awarded on a second or subsequent contract, changes made prior to awarding the subsequent contract are usually incorporated in the subsequent contract at the outset. The result is that the cost visibility of those changes is lost, and in fact the cost may actually be zero for some changes since the necessity for making a change during construction is eliminated and the detail design work has been paid for in the previous contract.

Figure 13 applies to a multiship acquisition program but only on a per ship basis. The cost of changes caused by design deficiencies is shown as a per-ship average, but the

Table 13. Average Cost of Contract Changes per Ship Caused by Deficiencies in Contract Plans and Specifications for Ships in the Initial Contract Award [6-14, 20-28].

Ship Class	Average Cost of Changes* per Ship $Millions	Average Ship Fiscal Year	Shipbuilding Cost Index	Average Cost of Changes* Per Ship in FY76 Dollars $Millions	Average Changes* per Ship in Percent of Average Ship Acquisition Cost
CG26-28	0.43	1965	2.51	1.08	0.77
CGN36-37	3.1	1972	1.66	5.15	1.58
CGN38-40[a]	2.4	1974	1.33	3.19	0.98
DD963-992[a]	0.14	1970	1.94	0.27	0.15
LSD37-40	0.16	1969	2.06	0.33	0.52
LKA113-116	0.21	1969	2.06	0.43	0.77
AE26-28	0.98	1967	2.29	2.24	2.76
AOR1-2	0.46	1970	1.94	0.90	1.22

Notes: Changes* are contract changes caused by deficiencies in contract plans and specifications.

a. Cost of changes as of January, 1976.

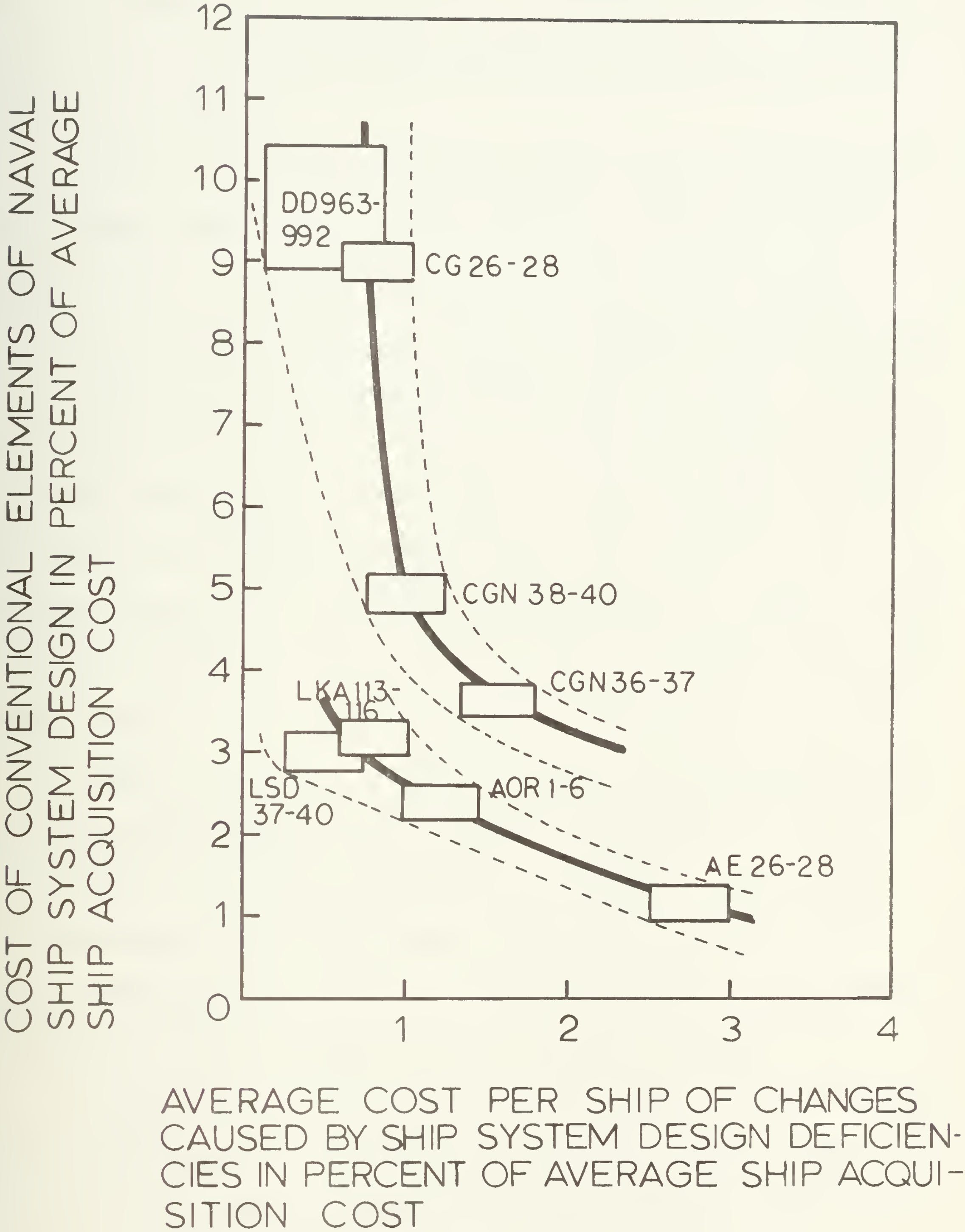

Figure 13. Naval Ship System Design Cost-Effectiveness Function Per Ship.

design costs shown are for the entire ship acquisition program. In order to use Figure 13 to determine the correct amount of design effort for a multiship contract, two more steps are necessary.

Figure 13 shows the average cost of changes per ship due to design deficiencies as a function of the level of design effort. In terms of total program costs, the cost of changes shown in Figure 13 must be multiplied by the number of ships in the contract for each point on the curve. The effect is to shift the point at which the slope is minus one. This reflects the fact that the correct level of design effort is affected by the size of buy. Alternatively, the design cost can be divided by the number of ships in the contract to place design cost on a per ship basis along with changes cost.

Figure 14 shows a family of curves for different size ship buys; developed by dividing the design cost shown in Figure 13 by the number of ships in the buy, and plotting the design cost per ship versus the cost of changes due to design deficiencies per ship, for each size buy. The point at which the slope is minus one is marked on each curve.

The final step is to plot the correct level of design effort (slope equal to minus one) for each size of buy. This has been done in Figure 15, along with the author's estimated error band. The error band is based on the author's estimate of repeatability of data. No allowance is made for possible error in the shipbuilding cost index developed in Chapter III.

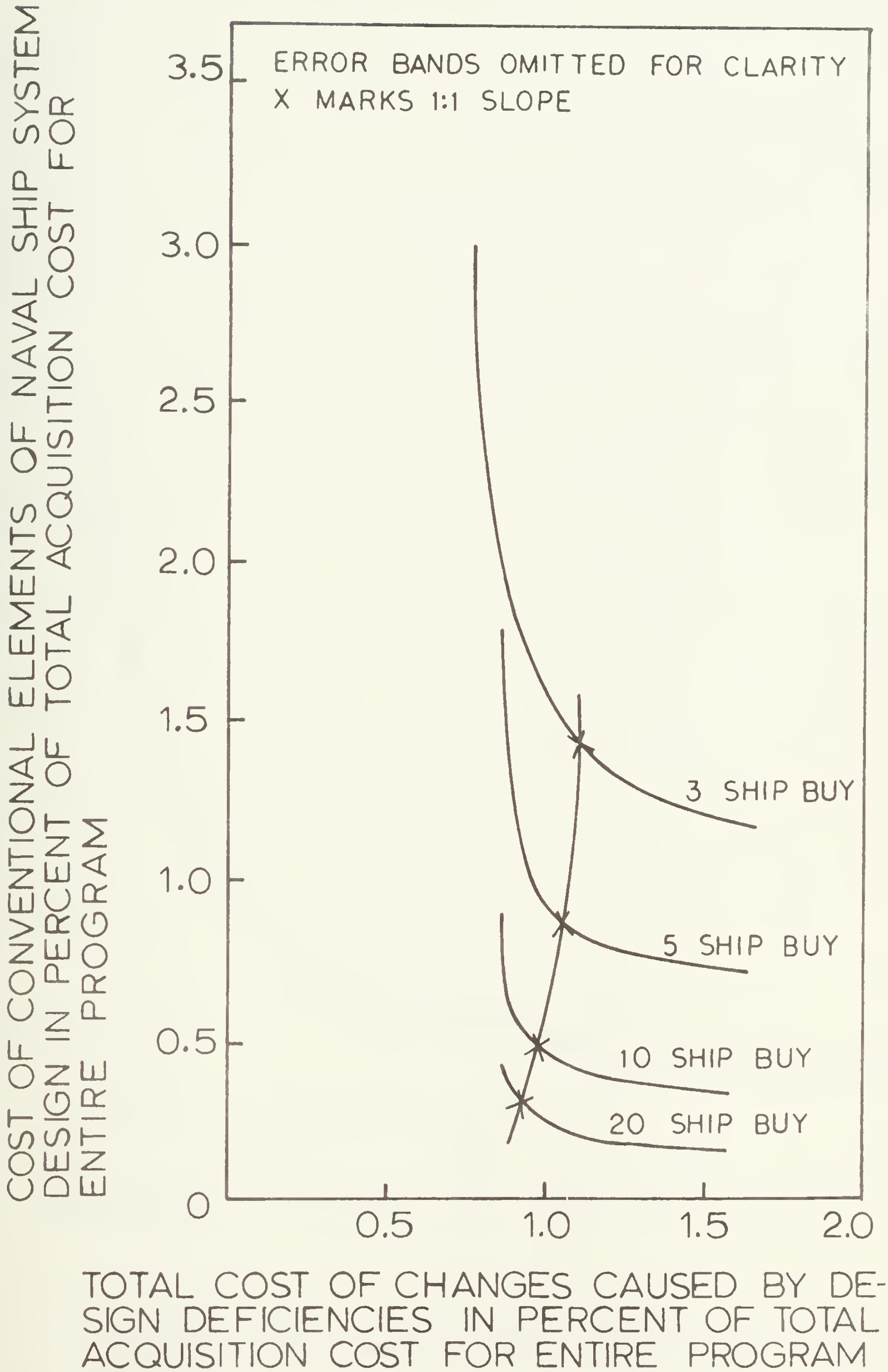

Figure 14. Naval Ship System Design Cost-Effectiveness Functions for Various Size Ship Buys of Combatant Ships.

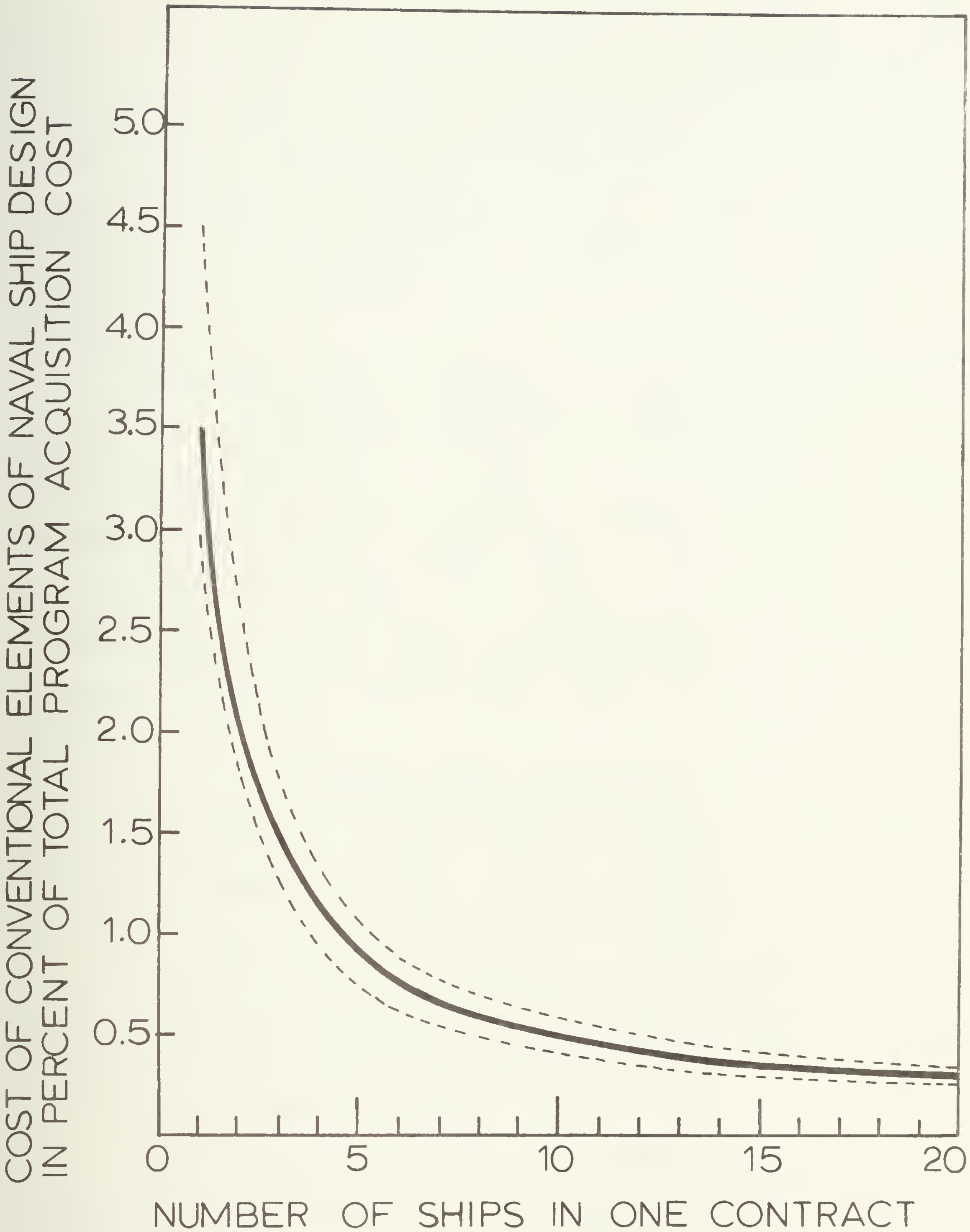

Figure 15. Optimal Level of Effort for Conventional Elements of Naval Ship System Design for Combatant Ships.

Figure 15 shows the optimal level of effort to expend on the conventional elements of Naval ship system design for any size buy up to 20 ships. Figure 15 applies only to combatant ships, and only to acquisition programs for which all ships are bought in a single contract. Figure 15 does not apply to the follow ships of a lead-follow acquisition strategy.

The curve shown in Figure 13 for non-combatant ships is too flat to allow development of a curve similar to Figure 15 for non-combatant ships. The point at which the minus one slope occurs is very near the left hand end of the curve shown in Figure 13. Expanding the changes axis by multiplying by the number of ships forces the point of minus one slope off the left hand end of the curve.

Summary and Conclusions

The cost of contract changes caused by design deficiencies has been presented. The costs have been adjusted for inflationary effect by means of a shipbuilding cost index, and the effect of ship system complexity has been taken into account by expressing the cost of changes in percent of ship acquisition cost.

Cost effectiveness functions were developed for both combatant and non-combatant lead ships or one ship buys. It was shown that the optimum level of effort to expend on the conventional elements of Naval ship system design is about 3 1/2 percent (+1, -1/2 percent) of lead ship acquisition

cost for combatant lead ships or one ship buys. This level of design effort would be optimal for a lead-follow acquisition program if and only if the cost of design deficiency changes is zero for the follow ships.

It was shown that the optimum level of effort to expend on the conventional elements of Naval ship system design is about 2 1/2 percent ($\pm$ 1/2 percent) of lead ship acquisition cost for non-combatant lead ships, or one ship buys. The recommended level of design effort would be optimal for a lead-follow acquisition program if and only if the cost of design deficiency changes is zero for the follow ships.

Present design capacity is sufficient to support an optimum level of effort; however, it is the author's opinion that the level of manning that can be effectively utilized must also be considered. Attempts to complete the design work in a shorter time by assigning more people to do the work will compound design management problems, result in more rework, and generally reduce the efficiency of the effort. In extreme cases, attempts to compress the design schedule will increase the probability of serious error, with consequent costly changes later, regardless of the amount of money spent or level of manpower devoted to the effort.

The optimal level of effort to expend on the conventional elements of Naval ship system design was developed for multiship buys of combatant ships. The optimal level of

effort varies from 0.4 percent to 4.5 percent of the total acquisition cost for the entire program depending on the number of ships bought on a single contract. It was not possible to develop the optimal level of design effort for multiship buys of non-combatant ships, due to the shape of the cost-effectiveness function for non-combatant ships.

It is concluded that acquisition cost can be reduced by expending the optimum level of effort on the conventional elements of Naval ship system design. The total acquisition cost, including the cost of design and the cost of changes caused by deficiencies in the contract plans and specifications, will increase if a non-optimum level of effort is expended on design. The effectiveness of non-conventional design tasks has not been addressed. No data exist as of the date of this study to assess the cost-effectiveness of ship system design for the follow-ship of a lead-follow acquisition approach.

Chapter V will summarize the findings of this thesis, state conclusions, present suggestions for using the information in this thesis, and make recommendations for further study.

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This chapter will present a summary of the thesis, state answers to the research questions, state general conclusions, and make suggestions for further study.

Summary

The objective of this thesis was to answer the primary research question of "What is the optimum level of design effort?" or "How much design is enough?" Corollary questions were:

1. Can acquisition cost be decreased by increasing the scope of design effort?
2. Does sufficient design capacity exist to support an increase in the scope of design effort?

Chapter II presented a brief overview of the different approaches to Naval ship system design. The ship system design tasks common to all the different approaches were identified and labeled the "conventional elements of Naval ship system design," or the "hard-core engineering design tasks of Naval ship system design."

Chapter III presented the cost of ship system design for twelve classes of Naval ships. It was shown that the total design effort has been increasing in both absolute terms and in percent of ship acquisition cost. The effort expended on the hard-core engineering tasks has been increasing in both absolute terms and in percent of ship acquisition cost, for non-combatant ships. The effort expended on the hard-core engineering tasks for combatant ships displays too much scatter to show any clear trend.

Chapter IV presented the cost of changes caused by deficiencies in contract plans and specifications. The cost of these changes was compared to the cost of the conventional elements of ship system design for each class, and a cost-effectiveness function was developed.

The data collected and presented in Chapter IV is affected by subjective judgment on the part of the author. The collection and analysis of the data was <u>not</u> a straightforward "look up the facts" effort. Several thousand contract change file folders had to be examined, and the contents of each folder had to be subjected to the author's judgment in determining whether or not the change was caused by a deficiency in contract plans and specifications. Considerable data manipulation was necessary throughout the thesis, to allow for inflationary effects and to make an allowance for differences in ship system complexity.

The shipbuilding cost index used is known to be imperfect. Error in the shipbuilding cost index can affect

the shape of the cost-effectiveness curves; consequently, the optimum level of design effort is also affected by error in the shipbuilding cost index. These facts should be kept in mind while considering the conclusions and recommendations to follow. The conclusions are based on more factual evidence than any previous study, but the factual evidence is not completely free of distorting influences.

Conclusions and Recommendations

The thesis has now reached a point where conclusions can be presented.

The first conclusion is that the level of effort expended on the conventional elements of Naval ship system design affects the cost of contract changes caused by deficiencies in the contract plans and specifications. The total ship acquisition cost, including the cost of ship system design, can be reduced by expending the optimum level of effort on the conventional elements of ship system design. Spending one unit less than the optimum will result in more than one unit increase in the cost of changes. Spending one unit more than the optimum will result in less than one unit saving in the cost of changes. The fact that an optimum exists is a direct consequence of the fact that the effectiveness of increasing levels of design effort exhibits decreasing marginal returns.

The second conclusion is that the optimum level of effort for the conventional elements of Naval ship system

design is about 3.5 percent (+ 1 percent, - 0.5 percent) of the lead ship acquisition cost for combatant lead ships or single ship contracts. This level of effort is recommended by the author. This level of effort is optimal only for the first ship of a new class of a reasonably well-known ship type; it does not apply to an updated design of an existing class, or to the design of a revolutionary ship type, or to the follow ships in a lead-follow acquisition program. The recommended level of effort is optimal for a lead-follow acquisition program if and only if the cost of changes caused by design deficiencies is zero for the follow ships.

The third conclusion is that the optimum level of effort for the conventional elements of Naval ship system design is about 2.5 percent (± 0.5 percent) of the lead ship acquisition cost for non-combatant lead ships or single ship contracts. This level of effort is recommended by the author. This level of effort is optimal only for the first ship of a new class of a reasonably well-known ship type; it does not apply to an updated design of an existing class, or to the follow ships in a lead-follow acquisition program. The recommended level of effort is optimal for a lead-follow acquisition program if and only if the cost of changes caused by design deficiencies is zero for the follow ships.

The fourth conclusion is that the optimum level of effort for the conventional elements of Naval ship system design for multiple-ship contracts for combatant ships

varies from 0.4 percent to 4.5 percent of total program cost, depending on the number of ships bought on one contract. Data limitations precluded development of a similar conclusion for non-combatant ships. Data does not exist for the follow ships in a lead-follow acquisition program.

The fifth conclusion is that sufficient ship system design capacity exists to implement the recommended level of design effort, based on the fact that several recent ship system designs have absorbed more effort than the recommended amount. It may be necessary to adjust design and acquisition program schedules somewhat to avoid overloading the design capacity, but the recommended level of effort is believed to be feasible.

It is the author's opinion that design and acquisition programs should be scheduled to maintain a constant design workload near design capacity, but care should be taken to avoid overloading the design capacity, particularly when the overload is due to an accelerated design schedule. Attempts to rush the design process will undoubtedly increase the probability of serious error, with consequent costly changes later, regardless of the amount of money spent or level of manpower devoted to the effort.

The sixth conclusion is that the total impact of expending a non-optimum level of effort on the conventional elements of ship system design is small. The potential return from an optimum level of design effort is worthwhile, but not large. The potential reduction in total acquisition

cost is less than three percent. If the design cost for the CG26 had been reduced by four percent of lead ship acquisition cost, the cost of changes would have increased by about one percent of lead ship acquisition cost, leaving a net saving of about three percent. If the design cost for the FFG7 or the AE26 had been increased by one percent of lead ship acquisition cost, the decrease in the cost of changes would have been less than two percent, leaving a net saving of less than one percent.

A three percent saving in a billion-dollar program is certainly worthwhile, but probably not as significant as savings that might result from other actions. Increasing the level of systems analysis effort in the selection of gross ship characteristics might well result in savings more significant than choosing the optimum level of effort to expend on hard-core engineering design tasks.

The return from increasing the level of effort expended on the non-conventional elements of ship system design, including systems analysis techniques, has not been determined. It is recommended that further research be conducted to determine the optimum level of effort to expend on the non-conventional elements of Naval ship system design. The results of that research, combined with the conclusions reached in this thesis, will provide a more complete answer to the question of "How much design (total) is enough?" The author suggests that the role of the non-conventional elements of ship system design in determining the "design to"

requirements, selecting the gross ship system characteristics, and reducing life cycle costs may be more significant than the role of the conventional elements in reducing the cost of changes.

Finally, additional research is recommended to determine the cost-effectiveness of reworking the contract plans and specifications for the follow ships in a lead-follow acquisition approach. It is a widely held opinion that rework of the contract design, incorporating all that has been learned from the detail design and construction of the lead ship, should significantly reduce the cost of changes in the follow-ships. The cost of reworking the contract design, and the effectiveness in reducing the cost of follow-ship changes should be determined. The total cost of contract design rework plus the cost of follow-ship changes caused by design deficiencies should be compared to the cost of follow-ship changes caused by design deficiencies when the contract design is <u>not</u> redone. Future data from the FFG7 program can be compared to the data presented in this thesis to determine whether or not the lead-follow acquisition approach is cost-effective. It is suggested that the value of "time-to-acquire" should be addressed by the same research effort.

The author believes that the information and recommendations contained in this thesis are worthy of consideration by Ship Design Managers and Ship Acquisition Project Managers. A worthwhile saving in total ship acquisition

cost can be achieved by using as a guide the recommendations presented here, tempered by experienced judgment and any unique requirements of the individual design and acquisition program. The author will be grateful if this work is accepted in that manner.

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